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# DERIVATION OF THE INTERNATIONAL GEOMAGNETIC REFERENCE FIELD

[GRF(10/68)]

(REVISED)

JOSEPH C. CAIN  
SHIRLEY J. CAIN

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by  
Joseph C. Cain  
and  
Shirley J. Cain

Goddard Space Flight Center  
Greenbelt, Maryland 20771

**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

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Joseph C. Cain and Shirley J. Cain  
*Goddard Space Flight Center*

## INTRODUCTION

This paper summarizes some of the computations that were made at the International Association of Geomagnetism and Aeronomy (IAGA) Symposium in Washington, D. C., October 22-25, 1968, that led to the resolution by the Working Group on the Analysis of the Geomagnetic Field (Reporter, A. J. Zmuda) to propose an International Geomagnetic Reference Field (IGRF). The basic requirements established by Dr. Zmuda following the discussion at previous meetings called for the IGRF to consist of no more than 80 spherical harmonic coefficients of internal origin, epoch 1965.0, each being tabulated together with its first time derivative. These coefficients were to represent true spherical harmonics describing the field, not "quasi-spherical" harmonics resulting from derivations neglecting the oblateness of the earth. Further, only sets of coefficients submitted to the Working Group on or prior to March 15, 1968, were to be considered.

These sets of spherical harmonic coefficients are given in Table 1. They are each updated to 1965.0 and are limited to an  $n^*$  (maximum degree  $n$  and order  $m$  of the spherical harmonic coefficients) of eight. Of the sets given, all except those in Tables 1(g) and 1(h) take into account the oblateness of the earth in their derivation. Most of the field descriptions appear in the World Magnetic Survey (WMS) Volume (Zmuda, 1971). However, a few have also been published separately, as follows.

<u>Table</u>	<u>Field Model</u>	<u>Reference</u>
1(a)	GSFC(12/66)	Cain et al., 1967
1(g)	USC&GS <sup>1</sup>	Hurwitz et al., 1966
1(h)	RGO-1 (LME) <sup>2</sup>	Leaton et al., 1965

<sup>1</sup>United States Coast & Geodetic Survey.

<sup>2</sup>Royal Greenwich Observatory (RGO) model 1, based on Leaton, Malin, and Evans (1965).

Table 1—Spherical harmonic coefficients and their derivatives.

EPOCH = 1965.0				GSFC(12/66) SET 1				EPOCH = 1965.0				AFCRL(3/68)			
<i>n</i>	<i>m</i>	<i>g</i>	<i>h</i>	<i>g</i>	<i>h</i>	<i>g</i>	<i>h</i>	<i>n</i>	<i>m</i>	<i>g</i>	<i>h</i>	<i>g</i>	<i>h</i>	<i>g</i>	<i>h</i>
1	0	-30333	0	13.7	0.0	-30339	0	1	0	-30339	0	12.0	0.0	12.0	0.0
1	1	-2117	5759	9.3	-3.9	-2133	5774	1	1	-2133	5774	6.7	-0.9	6.7	-0.9
2	0	-1660	0	-24.1	0.0	-1657	0	2	0	-1657	0	-27.6	0.0	-27.6	0.0
2	1	2997	-2002	-0.2	-14.0	2993	-2016	2	1	2993	-2016	-0.2	-15.9	-0.2	-15.9
2	2	1561	119	-5.8	-16.7	1579	140	2	2	1579	140	-3.6	-15.4	-3.6	-15.4
3	0	1299	0	-1.5	0.0	1302	0	3	0	1302	0	0.3	0.0	0.3	0.0
3	1	-2043	-397	-10.8	5.7	-2039	-409	3	1	-2039	-409	-10.2	5.0	-10.2	5.0
3	2	1289	240	2.4	2.5	1290	239	3	2	1290	239	1.2	2.1	1.2	2.1
3	3	847	-167	-6.8	-6.6	855	-195	3	3	855	-195	-6.8	-10.9	-6.8	-10.9
4	0	957	0	1.5	0.0	965	0	4	0	965	0	0.7	0.0	0.7	0.0
4	1	807	149	0.7	-2.2	807	142	4	1	807	142	0.8	-1.4	0.8	-1.4
4	2	495	-274	-1.7	0.1	495	-286	4	2	495	-286	-0.3	-1.4	-0.3	-1.4
4	3	-394	11	0.7	1.7	-391	1	4	3	-391	1	-0.5	-2.6	-0.5	-2.6
4	4	249	-280	-3.5	-6.8	269	-269	4	4	269	-269	-1.0	-4.4	-1.0	-4.4
5	0	-224	0	1.8	0.0	-220	0	5	0	-220	0	3.3	0.0	3.3	0.0
5	1	359	15	0.6	2.0	351	26	5	1	351	26	0.6	2.2	0.6	2.2
5	2	247	126	3.7	1.6	239	129	5	2	239	129	2.6	2.3	2.6	2.3
5	3	-29	-128	-0.0	-2.6	-26	-118	5	3	-26	-118	0.4	-1.8	0.4	-1.8
5	4	-161	-106	-0.5	0.5	-151	-117	5	4	-151	-117	1.6	-1.8	1.6	-1.8
5	5	-52	81	2.0	-0.2	-44	80	5	5	-44	80	4.0	-1.1	4.0	-1.1
6	0	47	0	-0.4	0.0	47	0	6	0	47	0	-1.2	0.0	-1.2	0.0
6	1	62	-11	0.9	0.1	56	-16	6	1	56	-16	-1.0	-0.5	-1.0	-0.5
6	2	4	105	0.9	0.0	7	104	6	2	7	104	0.5	0.1	0.5	0.1
6	3	-225	70	2.6	2.6	-237	68	6	3	-237	68	1.1	1.9	1.1	1.9
6	4	2	-30	0.8	-1.3	1	-27	6	4	1	-27	0.4	0.2	0.4	0.2
6	5	-1	-12	0.1	0.5	-12	-8	6	5	-12	-8	-2.7	0.6	-2.7	0.6
6	6	-107	-9	0.3	0.8	-103	-17	6	6	-103	-17	0.4	-0.4	0.4	-0.4
7	0	69	0	-0.6	0.0	75	0	7	0	75	0	0.2	0.0	0.2	0.0
7	1	-56	-59	-0.4	-1.0	-53	-52	7	1	-53	-52	-0.3	-0.6	-0.3	-0.6
7	2	0	-27	-1.6	0.1	-3	-30	7	2	-3	-30	-1.0	-0.8	-1.0	-0.8
7	3	11	-6	-0.9	0.5	20	-10	7	3	20	-10	0.8	0.9	0.8	0.9
7	4	-24	11	0.0	0.8	-27	4	7	4	-27	4	-0.5	-0.4	-0.5	-0.4
7	5	-7	22	-0.7	-0.4	-11	20	7	5	-11	20	-0.8	-0.4	-0.8	-0.4
7	6	15	-20	-0.2	0.6	6	-16	7	6	6	-16	0.7	1.7	0.7	1.7
7	7	0	-17	-0.7	1.0	-12	-15	7	7	-12	-15	-2.2	1.3	-2.2	1.3
8	0	10	0	0.4	0.0	9	0	8	0	9	0	-0.2	0.0	-0.2	0.0
8	1	9	3	0.5	-0.6	5	10	8	1	5	10	0.3	-0.3	0.3	-0.3
8	2	0	-13	1.9	-0.3	-5	-14	8	2	-5	-14	0.0	-0.2	0.0	-0.2
8	3	-10	4	-0.1	0.1	-15	13	8	3	-15	13	-0.7	-1.0	-0.7	-1.0
8	4	-4	-20	0.4	-0.8	-8	-15	8	4	-8	-15	-0.9	-0.4	-0.9	-0.4
8	5	5	5	-0.1	0.0	3	2	8	5	3	2	-0.2	-0.4	-0.2	-0.4
8	6	-6	22	0.5	0.1	-7	19	8	6	-7	19	-0.4	-0.2	-0.4	-0.2
8	7	12	-3	-0.2	-0.4	9	-4	8	7	9	-4	-1.7	-1.3	-1.7	-1.3
8	8	5	-19	-0.5	-0.4	8	-13	8	8	8	-13	-0.9	-0.7	-0.9	-0.7

TABLE 1(a)

TABLE 1(b)

IZMIRAN(3/68)

EPOCH = 1965.0

RG0(3/68)-2 (MALIN)

EPOCH = 1965.0

$n$	$m$	$g$	$h$	$\dot{g}$	$\dot{h}$	$n$	$m$	$g$	$h$	$\dot{g}$	$\dot{h}$
1	0	-30358	0	17.0	0.0	1	0	-30350	0	17.0	0.0
1	1	-2147	5706	9.0	0.0	1	1	-2115	5770	9.0	0.0
2	0	-1630	0	-24.0	0.0	2	0	-1640	0	-24.0	0.0
2	1	3000	-2015	-1.0	-12.0	2	1	2979	-2000	-1.0	-12.0
2	2	1552	201	2.0	-18.0	2	2	1585	115	2.0	-18.0
3	0	1297	0	0.0	0.0	3	0	1279	0	0.0	0.0
3	1	-2035	-391	-10.0	5.0	3	1	-2008	-425	-10.0	5.0
3	2	1289	264	-1.0	1.0	3	2	1289	241	-1.0	1.0
3	3	758	-229	-1.0	-9.0	3	3	862	-156	-1.0	-9.0
4	0	976	0	-1.0	0.0	4	0	940	0	-1.0	0.0
4	1	814	138	0.0	1.0	4	1	792	161	0.0	1.0
4	2	486	-308	-4.0	1.0	4	2	484	-280	-4.0	1.0
4	3	-388	-1	1.0	3.0	4	3	-389	11	1.0	3.0
4	4	266	-174	-3.0	-3.0	4	4	259	-254	-3.0	-3.0
5	0	-242	0	1.0	0.0	5	0	-207	0	1.0	0.0
5	1	344	-6	0.0	2.0	5	1	367	18	0.0	2.0
5	2	262	102	3.0	2.0	5	2	239	133	3.0	2.0
5	3	-5	-99	-1.0	-2.0	5	3	-28	-122	-1.0	-2.0
5	4	-174	-106	1.0	1.0	5	4	-166	-97	1.0	1.0
5	5	-42	52	0.0	0.0	5	5	-64	75	0.0	0.0
6	0	62	0	0.0	0.0	6	0	39	0	0.0	0.0
6	1	68	-18	0.0	-2.0	6	1	55	-17	0.0	-2.0
6	2	6	112	1.0	1.0	6	2	2	107	1.0	1.0
6	3	-226	76	2.0	2.0	6	3	-233	58	2.0	2.0
6	4	2	-58	0.0	-1.0	6	4	7	-31	0.0	-1.0
6	5	-20	5	0.0	0.0	6	5	3	-16	0.0	0.0
6	6	-160	-30	-1.0	1.0	6	6	-112	-10	-1.0	1.0
7	0	64	0	0.0	0.0	7	0	77	0	0.0	0.0
7	1	-55	-73	0.0	0.0	7	1	-47	-46	0.0	0.0
7	2	4	-27	0.0	0.0	7	2	2	-25	0.0	0.0
7	3	3	-14	0.0	0.0	7	3	12	-10	0.0	0.0
7	4	-19	12	0.0	0.0	7	4	-28	8	0.0	0.0
7	5	-8	31	0.0	0.0	7	5	-12	24	0.0	0.0
7	6	13	-16	0.0	0.0	7	6	15	-22	0.0	0.0
7	7	-10	-13	0.0	0.0	7	7	5	-21	0.0	0.0
8	0	16	0	0.0	0.0	8	0	6	0	0.0	0.0
8	1	10	4	0.0	0.0	8	1	13	-4	0.0	0.0
8	2	-9	-22	0.0	0.0	8	2	-6	-7	0.0	0.0
8	3	-10	2	0.0	0.0	8	3	-17	1	0.0	0.0
8	4	-6	-11	0.0	0.0	8	4	2	-16	0.0	0.0
8	5	18	-2	0.0	0.0	8	5	10	5	0.0	0.0
8	6	8	26	0.0	0.0	8	6	-5	24	0.0	0.0
8	7	16	-10	0.0	0.0	8	7	12	4	0.0	0.0
8	8	8	-8	0.0	0.0	8	8	6	-15	0.0	0.0

TABLE 1(d)

TABLE 1(c)

EPOCH = 1965.0				EPOCH = 1965.0				AFCRL(11/67)			
P060(3/68)											
$n$	$m$	$g$	$h$	$\dot{g}$	$\dot{h}$	$n$	$m$	$g$	$h$	$\dot{g}$	$\dot{h}$
1	0	-30338	0	26.2	0.0	1	0	-30332	0	12.4	0.0
1	1	-2112	5770	4.7	-6.1	1	1	-2137	5791	6.3	0.0
2	0	-1661	0	-23.3	0.0	2	0	-1658	0	-27.5	0.0
2	1	2999	-2011	2.3	-9.0	2	1	2992	-2002	-0.3	-13.8
2	2	1595	123	11.8	-8.8	2	2	1573	142	-3.0	-13.9
3	0	1302	0	-8.2	0.0	3	0	1306	0	0.3	0.0
3	1	-2043	-406	-9.3	10.7	3	1	-2035	-404	-9.7	4.0
3	2	1299	239	-0.8	2.6	3	2	1294	250	1.4	3.3
3	3	856	-160	-11.0	0.8	3	3	866	-184	-4.5	-12.0
4	0	955	0	-0.3	0.0	4	0	954	0	-0.3	0.0
4	1	803	152	-1.5	4.3	4	1	812	139	0.9	-1.9
4	2	478	-275	-6.0	-0.8	4	2	491	-288	0.4	-2.1
4	3	-382	15	-6.3	2.9	4	3	-384	6	-0.9	3.4
4	4	254	-230	-3.3	-14.2	4	4	275	-272	-0.4	-3.2
5	0	-222	0	3.8	0.0	5	0	-229	0	2.5	0.0
5	1	361	19	-0.5	-1.0	5	1	354	17	1.1	1.4
5	2	247	127	1.2	1.1	5	2	241	120	2.5	0.5
5	3	-33	-126	1.8	-4.5	5	3	-28	-129	0.4	-3.0
5	4	-168	-98	-3.5	0.7	5	4	-144	-110	3.1	-1.9
5	5	-54	76	1.2	-5.3	5	5	-53	71	4.5	-0.3
6	0	46	0	-0.3	0.0	6	0	46	0	-1.6	0.0
6	1	62	-11	0.9	-1.0	6	1	59	-5	-1.3	1.7
6	2	11	106	2.1	-0.5	6	2	7	109	-0.3	1.5
6	3	-233	68	5.7	0.5	6	3	-244	68	0.9	1.5
6	4	3	-45	0.6	2.0	6	4	-6	-35	-0.5	-0.6
6	5	-12	3	2.1	0.8	6	5	-1	-14	-2.1	-0.5
6	6	-144	-25	-3.9	0.1	6	6	-92	-17	1.5	-0.9
7	0	72	0	-0.9	0.0	7	0	76	0	1.1	0.0
7	1	-53	-63	0.0	-0.5	7	1	-52	-57	-0.0	-1.1
7	2	3	-27	0.1	0.8	7	2	-2	-25	-1.0	-0.9
7	3	14	-8	-0.8	0.5	7	3	19	-15	-1.1	0.5
7	4	-22	7	2.5	1.2	7	4	-32	5	-1.1	-1.0
7	5	-6	24	0.4	1.2	7	5	-19	20	-1.5	-0.5
7	6	12	-19	0.2	-0.6	7	6	10	-24	1.0	1.5
7	7	-10	-19	1.4	1.9	7	7	-7	-22	-2.3	0.9
8	0	10	0	0.4	0.0	8	0	14	0	-0.4	0.0
8	1	3	10	0.4	0.4	8	1	7	9	0.6	0.2
8	2	-4	-13	0.5	-0.2	8	2	-5	-6	0.3	0.8
8	3	-10	8	-1.5	-0.5	8	3	-16	18	-0.2	-0.5
8	4	-5	-13	-0.6	-1.6	8	4	-2	-22	-0.6	-0.0
8	5	14	-1	-0.7	0.0	8	5	2	5	-0.7	-1.1
8	6	5	26	1.5	0.1	8	6	-3	16	-0.5	-1.5
8	7	15	-10	0.4	-0.1	8	7	2	7	-1.9	-1.9
8	8	9	-11	-2.6	1.1	8	8	0	-25	-0.7	-3.4

TABLE 1(e)

TABLE 1(f)

EPOCH = 1965.0 USCGS(5/66&3/68)

RCO(3/68)-1(L.F.A.T.O.N), BASED ON LINE

EPOCH = 1965.0

USCGS(5/66&3/68)

n	m	g	h	g	h	n	m	g	h	g	h
1	0	-30372	0	15.5	0.0	1	0	-30388	0	15.0	0.0
1	1	-2083	5781	8.3	0.6	1	1	-2117	5760	10.5	-4.0
2	0	-1635	0	-26.6	0.0	2	0	-1637	0	-21.1	0.0
2	1	2949	-1993	-1.3	-11.4	2	1	2981	-2004	2.7	-7.1
2	2	1582	108	1.3	-18.2	2	2	1583	127	0.5	-17.8
3	0	1161	0	0.0	0.0	3	0	1153	0	1.3	0.0
3	1	-2025	-405	-9.5	3.2	3	1	-1989	-425	-14.1	1.1
3	2	1291	238	-1.9	1.6	3	2	1282	243	0.9	-3.0
3	3	872	-148	-0.6	-8.5	3	3	855	-161	-2.5	-6.2
4	0	930	0	0.6	0.0	4	0	925	0	-4.8	0.0
4	1	809	153	1.0	3.0	4	1	806	148	-0.8	0.3
4	2	489	-274	-2.2	-0.7	4	2	489	-293	-6.6	7.3
4	3	-395	8	0.2	2.7	4	3	-382	11	-1.8	4.6
4	4	262	-257	-3.0	-2.7	4	4	256	-249	-1.8	-5.0
5	0	-179	0	0.8	0.0	5	0	-203	0	2.6	0.0
5	1	360	21	0.4	1.9	5	1	348	10	4.0	4.9
5	2	249	135	1.6	2.3	5	2	242	135	3.8	1.4
5	3	-13	-121	-0.3	-1.8	5	3	-31	-122	3.8	-4.3
5	4	-174	-100	-1.1	1.4	5	4	-158	-95	0.8	4.2
5	5	-63	74	1.7	0.5	5	5	-66	76	-0.8	-1.4
6	0	39	0	0.0	0.0	6	0	58	0	1.7	0.0
6	1	56	-18	-0.5	-2.2	6	1	71	-16	-1.6	-1.9
6	2	11	102	1.8	0.2	6	2	1	108	2.3	-3.3
6	3	-244	59	1.4	0.9	6	3	-232	55	2.3	2.8
6	4	21	-38	0.6	-2.1	6	4	-3	-23	-3.8	-3.2
6	5	8	-21	0.2	-0.1	6	5	1	-13	0.5	-0.6
6	6	-116	-9	-2.2	-0.2	6	6	-108	-13	-0.8	3.2
7	0	81	0	0.0	0.0	7	0	76	0	-2.1	0.0
7	1	-54	-48	0.0	0.0	7	1	-33	-36	-0.9	-3.8
7	2	7	-32	0.0	0.0	7	2	4	-14	-0.9	2.2
7	3	10	-14	0.0	0.0	7	3	14	-10	-2.4	0.6
7	4	-36	6	0.0	0.0	7	4	-25	8	1.8	0.6
7	5	-15	24	0.0	0.0	7	5	-14	25	1.4	2.8
7	6	11	-21	0.0	0.0	7	6	20	-24	-1.5	-1.2
7	7	4	-24	0.0	0.0	7	7	6	-18	-0.1	-0.9
8	0	8	0	0.0	0.0	8	0	3	0	0.4	0.0
8	1	18	2	0.0	0.0	8	1	12	-11	1.2	1.4
8	2	-8	-5	0.0	0.0	8	2	-3	-6	0.9	-0.4
8	3	-20	7	0.0	0.0	8	3	-21	-3	1.1	-0.7
8	4	6	-18	0.0	0.0	8	4	0	-15	-0.1	0.3
8	5	19	9	0.0	0.0	8	5	3	2	0.1	-1.3
8	6	-3	27	0.0	0.0	8	6	-8	20	1.4	-1.9
8	7	10	10	0.0	0.0	8	7	14	0	0.3	0.2
8	8	4	-14	0.0	0.0	8	8	8	-16	-1.1	-0.2

TABLE 1(h)

TABLE 1(g)



## TEST DATA

Although no explicit formula was agreed upon prior to the meeting for the derivation of an IGRF, there was an understanding that the model had to correspond to the available survey data.

Since the epoch of this IGRF was 1965, data were arbitrarily cut off at 1961, a year chosen so the results would not be too heavily weighted by observations prior to 1965. Testing was done on all data available since that date. These were divided into the major categories below.

- (1) Observatory annual means of surface magnetic fields, 1961-1967.
- (2) Surface magnetic surveys. This category includes land surveys, repeat stations, shipboard and ship-towed observations.
- (3) Aeromagnetic survey of Japan, 1965 (Nagata, 1966).
- (4) Aeromagnetic survey of Canada, 1961-1963.
- (5) Aeromagnetic survey of Scandinavia, 1965 (Eleman et al., 1969).
- (6) Project MAGNET worldwide (principally oceanic) airborne survey, 1961-1966 (USNOO, 1965).
- (7) OGO 2 data, as available during magnetically quiet intervals, October 1965 to September 1967.
- (8) OGO 4 data during magnetically quiet intervals from July to December 1967.
- (9) 1964-83c observations, 1964-1965 (Zmuda et al., 1968).
- (10) Cosmos 49 observations, 1964.8 (Dolginov et al., 1967).
- (11) Other airborne (towed proton-magnetometer) data.

All of the nonsatellite data were obtained from the file prepared by the Geomagnetic Division of the U.S. Coast and Geodetic Survey (E. Fabiano and S. Cain, WMS Volume). This file contained the contributions from many separate organizations and survey groups and is constantly updated as new observations are submitted. This file was edited by rejecting those observations deviating by more than  $1000\gamma$  from the GSFC(12/66) model (using  $n^* = 10$ ). This procedure was used to eliminate the highly anomalous data beyond about five times the root-mean-square (rms) deviation. Since all models were truncated to  $n^* = 8$  for testing, no particular advantage was given to GSFC(12/66). This model was used since it fitted the data set best; hence, it requires the least elimination of data. The amount rejected was small, as seen in Table 2.

The OGO 2 and OGO 4 data (sampled every 30 seconds or at a spacing of approximately 200 km) were initially selected from periods of time for which  $K_p = 0$ . They were then fit with a special model listed in Table 3(a) [POGO(10/68)] employing 143 internal coefficients and their first time derivatives. The distribution of deviations of the data from this fit was as follows.

$ \Delta F \gamma$	0	10	20	30	40	50	60	70	100	200	600	Total
Obs.	27,646	4218	589	141	23	26	6	2	9	4		32,664

Since the distribution indicated that they were probably anomalous, the 15 observations over  $70\gamma$  were rejected and the resulting rms deviation computed to be  $7\gamma$ . The remaining 32,649 observations were included in the testing.

The Cosmos 49 data were similarly treated by fitting with a special function and eliminating those data that deviated significantly from the rest. The data were prepared by the U.S. Coast and Geodetic Survey from the catalog (Dolginov et al., 1967) published by the Institute of Terrestrial Magnetism and Radiowave Propagation (IZMIRAN). These were sorted into time order and each fourth observation fit with a series of 99 spherical harmonic coefficients by a model labelled COSMOS(9/68), listed in Table 3(b). Data deviating more than  $100\gamma$  from the fitting surface were rejected in the coefficient determination. The distribution of residuals from this model, COSMOS(9/68), is as follows.

$ \Delta F \gamma$	0	10	20	30	40	50	60	70	80	90	100	Total
Obs.	1853	1243	648	271	93	41	23	18	19	15	138	4362

The use of every fourth observation in the fit is adequate since each orbit then contains about 10 observations for the shortest wavelength of the fitting function used ( $n^* = 9$  corresponds to  $360^\circ/9 = 40^\circ$ ). Since the rms deviation of these data from the COSMOS(9/68) field was  $21\gamma$ , the selection used for model testing consisted of those deviating by less than  $60\gamma$ , a total of 16,554 observations from the approximately 18,000 originally available.

The 1964-83c observations entered the testing unedited except for the rejection of one spurious point that gave a  $|\Delta F| > 1000\gamma$ .

Table 2—Nonsatellite data eliminated for  $\Delta C > 1000\gamma$ .

Data Type	Component Observations*	Data Rejected	
		Number	Percent
(1) Observatory	1984	34	1.7
(2) Surface	22,425	204	.9
(3) Japanese Air	1461	6	.4
(4) Canadian Air	9470	27	.3
(5) Scandinavian Air	6973	1	.01
(6) Project MAGNET	104,228	401	.4
(7) Other Air	1763	9	.5

\*In this and ensuing discussion a value of  $D$ ,  $I$ ,  $H$ ,  $Z$ , or  $F$  is counted as one observation even though other values may have been measured at the same time and location.

Table 3(a)—POGO(10/68) spherical harmonic coefficients and their time derivatives (Epoch 1960.0).

<i>n</i>	<i>m</i>	<i>g</i>	<i>h</i>	$\dot{g}$	$\dot{h}$	<i>n</i>	<i>m</i>	<i>g</i>	<i>h</i>	$\dot{g}$	$\dot{h}$
1	0	-30465.0		25.42		9	0	11.0		-0.24	
1	1	-2163.3	5791.0	9.88	-4.66	9	1	6.6	-20.4	0.30	-0.38
2	0	-1541.4		-23.90		9	2	1.8	14.4	0.04	0.16
2	1	2976.3	-1977.2	3.50	-7.07	9	3	-12.5	0.6	0.04	0.67
2	2	1607.5	156.6	-2.14	-10.70	9	4	15.8	-1.5	-0.40	-0.14
3	0	1325.8		-5.59		9	5	1.7	1.4	-0.28	-0.83
3	1	-1983.7	-445.3	-11.52	8.48	9	6	2.6	3.4	-0.57	1.30
3	2	1316.9	233.4	-4.41	0.68	9	7	8.7	14.8	-1.32	-0.33
3	3	842.0	-94.9	2.87	-14.89	9	8	5.1	2.4	-0.14	-0.38
4	0	959.1		-0.62		9	9	-2.4	-0.9	0.50	0.99
4	1	819.6	135.4	-2.51	3.45	10	0	-2.6		-0.01	
4	2	486.4	-266.7	-1.22	-0.39	10	1	-2.0	1.1	-0.09	0.21
4	3	-372.4	20.7	-2.95	-0.87	10	2	1.0	0.9	0.12	0.05
4	4	256.2	-241.5	0.86	-6.52	10	3	-5.5	-0.3	0.19	0.54
5	0	-234.3		2.72		10	4	-0.7	7.5	-0.20	-0.26
5	1	357.7	16.9	0.48	0.05	10	5	7.5	-2.3	-0.02	-0.30
5	2	233.9	113.3	3.17	3.00	10	6	7.8	1.4	-0.43	-0.03
5	3	-21.0	-128.7	-2.46	0.32	10	7	1.7	-0.5	-0.33	-0.39
5	4	-147.1	-115.1	-0.89	3.11	10	8	-5.3	4.3	1.03	-0.02
5	5	-45.2	130.3	-3.15	-6.35	10	9	1.3	8.0	0.22	-1.04
6	0	49.1		-0.61		10	10	-2.7	-13.7	0.46	0.79
6	1	54.5	-9.6	1.06	-0.26	11	0	2.3		0.03	
6	2	4.8	106.4	0.62	-0.48	11	1	-1.8	-0.8	0.11	0.35
6	3	-249.1	56.8	3.95	2.58	11	2	-2.1	4.4	0.05	-0.26
6	4	1.7	-27.2	-0.94	-0.80	11	3	5.5	-0.1	-0.30	-0.17
6	5	-3.7	-14.9	1.49	0.50	11	4	-1.5	-3.9	0.01	0.17
6	6	-91.6	-4.3	-1.67	0.82	11	5	2.4	-0.6	-0.34	0.18
7	0	75.9		-0.89		11	6	-3.5	1.8	0.48	-0.50
7	1	-52.4	-57.9	-0.21	-0.87	11	7	-1.3	-3.2	0.52	0.23
7	2	8.0	-25.0	-1.08	-0.46	11	8	2.5	0.8	-0.19	-0.34
7	3	10.0	-0.8	0.70	-1.02	11	9	-1.2	-5.9	-0.03	0.37
7	4	-36.7	6.3	1.07	0.25	11	10	12.7	-1.7	-1.65	0.22
7	5	-8.3	9.5	0.96	1.88	11	11	5.0	10.5	-0.40	-1.55
7	6	6.6	-11.7	1.01	-2.43						
7	7	-22.7	-37.6	5.23	2.32						
8	0	7.4		0.61							
8	1	6.0	10.1	-0.12	-0.15						
8	2	-8.1	-13.0	0.87	-0.10						
8	3	-9.2	11.5	-0.33	-1.22						
8	4	-0.8	-16.4	-0.14	-0.26						
8	5	9.1	5.5	-0.85	0.15						
8	6	-11.4	22.3	0.99	-0.37						
8	7	7.9	-4.9	0.81	0.29						
8	8	35.1	-26.2	-4.98	0.91						

$$g(t) = g + \dot{g}(t - 1960)$$

$$h(t) = h + \dot{h}(t - 1960)$$

## TEST RESULTS

The various models were tested against the data sets both with the limitation of 80 coefficients and also using all coefficients if more were available. Table 4(a) illustrates for the GSFC(12/66) model the distribution of residuals using the first 80 coefficients as well as the full number. Since the surface data were edited with this model using a 100 $\gamma$  criterion, there can be no residuals above this figure with 120 coefficients. The effect of the truncation is to increase the rms residuals by 10 $\gamma$ -20 $\gamma$  independent of their magnitude. Using 80 terms has only a small percentage effect on the surface data since magnetic anomalies account for a great deal of the scatter. The consequences for the satellite data are more obvious as seen in the OGO 2 results. Here the effect is to increase the number of residuals in the 50 $\gamma$ -100 $\gamma$  range from 5 to 10 percent of the total data, and to push the number over 100 $\gamma$  from 1 to 3 percent.

Table 3(b)—COSMOS(9/68) spherical harmonic coefficients.

<i>n</i>	<i>m</i>	<i>g</i>	<i>h</i>	<i>n</i>	<i>m</i>	<i>g</i>	<i>h</i>
1	0	-30415.2		7	0	30.3	
1	1	-2143.1	5721.6	7	1	-52.4	-70.2
2	0	-1640.5		7	2	4.5	-28.2
2	1	3001.9	-2014.4	7	3	5.4	-14.2
2	2	1556.8	189.2	7	4	-20.3	13.3
3	0	1211.1		7	5	-9.1	29.6
3	1	-2033.8	-388.6	7	6	11.8	-15.6
3	2	1286.4	258.0	7	7	-12.1	-15.4
3	3	780.0	-233.8	8	0	15.5	
4	0	969.6		8	1	11.1	3.8
4	1	816.3	137.6	8	2	-8.5	-21.1
4	2	487.2	-301.9	8	3	-9.3	2.2
4	3	-386.7	0.5	8	4	-6.8	-12.2
4	4	253.6	-186.4	8	5	17.0	-1.6
5	0	-299.4		8	6	7.7	27.1
5	1	348.5	-0.5	8	7	16.6	-9.3
5	2	264.3	106.7	8	8	7.9	-6.5
5	3	-12.4	-98.3	9	0	-9.1	
5	4	-172.3	-108.3	9	1	7.2	-29.3
5	5	-35.5	57.0	9	2	11.0	5.6
6	0	57.6		9	3	-14.6	13.5
6	1	69.2	-19.1	9	4	9.5	-2.3
6	2	5.9	110.4	9	5	2.5	-5.1
6	3	-228.1	74.9	9	6	0.7	6.4
6	4	6.4	-56.0	9	7	3.9	9.6
6	5	-19.4	3.3	9	8	3.3	-1.7
6	6	-158.9	-33.8	9	9	-2.3	0.5

These distributions were also calculated for each of the other test models, and the rms values compiled in Table 4(b). Here the correspondence of each data set to a model can be readily observed.

Although for each model there is an improvement with an increase in the number of coefficients, the difference is generally smaller for those groups of observations with higher average residuals.

## WEIGHTING OF IGRF

It was decided that a weighted average of coefficients would provide the best compromise for an IGRF. Due to the restriction that models to be included should be based on truly spherical coefficients, the RGO(LME) and USC&GS models were eliminated from the main field averaging. Since the surface-data residuals were so greatly influenced by crustal anomalies, it was decided to base these weights on the residuals to the satellite data.

Several different weighting schemes were tried. Generally, the precise choice of weights used did not alter the overall results appreciably as long as those models best fitting the satellite data were given preference. The POGO(3/68) and AFCRL(11/67) models were eliminated from the considerations since each organization submitted another model.

After the presentation of several semiquantitative arguments that the IGRF would be most useful circa 1965.0, the following tabulation of relative weights was agreed upon. Each weight was applied as an inverse square factor in combining the main field terms.



Model	$\sigma$ (weight, in $\gamma$ )
GSFC(12/66)	40
AFCRL(3/68)	70
RGO(3/68)-2	80
IZMIRAN(3/68)	100

The GSFC model was given the  $40\gamma$  weight (even though it had a  $61\gamma$  residual to the OGO 4 data) because the OGO 2 figure was  $39\gamma$ , the other satellite residuals were low, and it has the overall lowest residuals to the surface data. The AFCRL model and RGO contributions were roughly equivalent but the AFCRL was given a slightly smaller weight because of its lower residual to OGO 2, Cosmos 49, and the surface data. The IZMIRAN model was assigned a slightly higher weight because of its uncertainty in the polar regions, the model being derived from data at less than  $50^\circ$  latitude. This decision is supported by the model's relatively high residuals to data sets containing polar contributions (e.g., OGO 2, OGO 4, observatory, land/sea, Scandinavian airborne, and Project MAGNET).

There was less basis for rational comparisons in combining the secular change terms. Hence each model previously used was weighted equally, and the USC&GS and RGO-1 models were included since the secular change was independently derived for each.

Although more lengthy considerations may have resulted in an improved procedure for deriving the first IGRF, this formulation provided a model composed of some contribution from each organization. At the same time, within the restrictions on the number of coefficients, it produced a model which agrees tolerably well with the test data set. This agreement is seen in the last column of Table 4. Surprisingly, the procedure appeared to produce a residual equal to or less than that of the contributing models for some of the data sets at the  $n^* = 8$  truncation level.

## THE RESULTING MODEL IGRF(10/68)

Since the IGRF is a composite of several models, it can be compared with each, as in Table 5. Here is listed for each of the contributing coefficient sets the deviation from the resulting IGRF. Although the disagreements between the various terms are sometimes relatively large for those with amplitudes of the order of  $1\gamma$  to  $10\gamma$ , those of higher magnitude are surprisingly close to one another. Of the main field terms, the largest discrepancy seems to be among those having  $m = n$ .

The final IGRF(10/68) coefficients are given in Table 6. Maps of the field and its secular change are given in Appendix 1. Appendix 2 gives a possible minor modification based on a suggested change of scale to a standard mean earth radius of 6371 in place of 6371.2 km.

## OBSERVATIONS AND RECOMMENDATIONS

It is appropriate at this point to make some observations on the domain of applicability of the international reference field and on its deficiencies and limitations. As can be seen in this report



Table 4(a)—Distribution of residuals from GSFC(12/66) using  $n^* = 8$  (80 coefficients) and  $n^* = 10$  (120 coefficients).

Data Type	Number of Coefficients	Residual Range ( $\gamma$ )						Total Number of Observations	rms ( $\gamma$ )
		0	50	100	250	500	1000		
Observatory	120 80	740 490	414 499	532 653	205 227	59 81	0 0	1950	187 198
Land/Sea	120 80	7089 5202	5418 4686	7071 8778	2081 2876	562 660	0 19	22,221	180 202
Japanese Air	120 80	362 331	301 274	491 504	252 294	49 51	0 1	1455	211 226
Canadian Air	120 80	2112 1865	1935 1683	3633 3593	1516 1974	247 328	0 0	9443	202 225
Scandinavian Air	120 80	2113 1715	1718 1560	2573 2889	537 776	31 32	0 0	6972	145 162
Project MAGNET	120 80	28,130 23,967	23,357 21,834	37,245 39,609	13,003 15,987	2101 2397	0 33	103,827	186 200
Cosmos 49	120 80	15,446 11,557	1095 4463	13 534	0 0	0 0	0 0	16,554	27 48
1964-83c	120 80	1242 1206	75 112	13 12	0 0	0 0	0 0	1330	28 32
OGO 2	120 80	18,296 16,878	948 2022	249 592	0 1	0 0	0 0	19,493	27 39
OGO 4	120 80	9300 8448	3037 3363	819 1341	0 2	0 0	0 0	13,156	51 61

Table 4(b)—Root-mean-square deviations of test data from various models using  $n^* = 8$  and  $n^* = \text{maximum degree and order of expansions}$ .

Data Type	Data	$n^*$	GSFC 12/66	POGO 3/68	POGO 10/68	AFCRL		RGO-1(LME)	RGO-2(Malin)	IZMIRAN	USC&GS	IGRF 10/68
						11/67	3/68					
Observatory	1950	8 max	198 187	211 204	203 193	208 201	208 197	223	202	272 271	245 236	196
Land/Sea	22,221	8 max	202 180	203 186	207 187	214 209	204 192	290	253	258 248	331 323	201
Japanese Air	1455	8 max	226 211	234 215	239 220	223 216	243 221	249	255	259 244	276 233	227
Canadian Air	9443	8 max	225 202	227 209	226 205	240 212	238 221	230	223	234 237	249 236	223
Scandinavian Air	6972	8 max	162 145	159 138	159 140	163 150	178 164	185	162	255 253	197 190	167
Project MAGNET	103,827	8 max	200 186	232 221	215 202	216 217	209 204	234	216	330 325	244 237	201
Cosmos 49	16,554	8 max	48 27	49 30	51 21	80 77	67 61	149	99	47 19	146 139	50
1964-83c	1330	8 max	32 27	34 31	33 29	68 67	47 45	85	58	33 31	10 93	32
OGO 2	19,493	8 max	39 28	28 11	30 7	52 47	57 49	98	66	94 94	110 108	39
OGO 4	13,156	8 max	61 51	39 15	40 9	85 82	89 80	126	89	114 114	144 142	57
Max. value of $n^*$			10	9	11	10	10	8	8	9	12	8

Table 5—Deviations from IGRF(10/68).

<i>g</i>								
<i>n</i>	<i>m</i>	GSFC(12/66)	AFCRL(3/68)	RGO-2	IZMIRAN	USCGS	RGO-1	IGRF
1	0	6	0	-11	-20	0	6	-30339
1	1	5	-10	8	-25	11	-15	-2123
2	0	-6	-3	14	24	-7	-3	-1654
2	1	3	-1	-15	6	5	-2	2994
2	2	-6	12	18	-15	28	6	1567
3	0	3	5	-18	1	5	10	1297
3	1	-6	-3	28	2	-6	1	-2036
3	2	0	1	0	0	10	5	1289
3	3	5	13	19	-85	14	24	843
4	0	-1	7	-18	18	-2	-4	958
4	1	2	1	-13	9	-2	7	805
4	2	2	2	-8	-7	-15	-1	492
4	3	-2	1	3	4	11	8	-392
4	4	-7	14	3	10	-1	20	256
5	0	-2	3	16	-19	0	-7	-223
5	1	2	-6	10	-13	3	-4	357
5	2	1	-7	-7	17	1	-4	246
5	3	-3	0	-2	21	-7	-2	-26
5	4	0	10	-5	-13	-7	17	-161
5	5	-1	7	-13	9	-3	-2	-51
6	0	0	-1	-8	15	-1	-1	47
6	1	2	-5	-5	8	1	-1	60
6	2	-1	2	-2	2	6	3	4
6	3	3	-8	-4	3	-4	-15	-229
6	4	0	-2	-4	-1	0	-9	3
6	5	3	-8	7	-16	-7	3	-4
6	6	5	9	0	-48	-32	20	-112
7	0	-2	4	6	-7	1	5	71
7	1	-2	1	7	-1	1	2	-54
7	2	0	-3	2	4	4	-2	0
7	3	-1	8	0	-9	2	7	12
7	4	1	-2	-3	6	2	-7	-25
7	5	1	-2	-3	1	3	-11	-9
7	6	2	-7	2	0	-1	-3	13
7	7	3	-10	7	-8	-7	-5	-2
8	0	0	-1	-4	6	0	4	10
8	1	0	-4	4	1	-6	-2	9
8	2	3	-2	-3	-6	-2	-2	-3
8	3	2	-2	-5	2	2	-4	-12
8	4	0	-4	6	-2	-1	2	-4
8	5	-2	-3	3	11	7	-4	7
8	6	-1	-2	0	13	9	1	-5
8	7	0	-3	0	4	3	-10	12
8	8	-1	2	0	2	3	-6	6

TABLE 5(a)

and others (Cain et al., 1965; Cain et al., 1967; Cain and Hendricks, 1968), ambient values of the earth's field depend on contributions from the core, crust, subsurface, and ionospheric electric currents; and from the effects of trapped plasma, magnetospheric boundary, and tail effects. The precise secular variation is subject to shifts which make a linear fit with time increasingly uncertain beyond a few years. Further, even for the decade of validity of the IGRF, 1960-1969, we know that there are more accurate models available.

$n$	$h$ $m$	GSFC(12/66)	AFCRL(3/68)	RGO-2	IZMIRAN	USCGS	RGO-1	IGRF
1	0	0	0	0	0	0	0	0
1	1	0	16	12	-52	11	32	5750
2	0	0	0	0	0	0	0	0
2	1	4	-11	6	-9	-6	4	-2006
2	2	-11	10	-15	71	-7	12	130
3	0	0	0	0	0	0	0	0
3	1	6	-6	-22	12	-3	-2	-403
3	2	-2	-3	-1	22	-3	7	242
3	3	10	-19	20	-53	16	-8	-176
4	0	0	0	0	0	0	0	0
4	1	1	-6	12	-10	4	-10	149
4	2	6	-6	0	-28	5	-8	-280
4	3	3	-7	3	-9	7	-2	8
4	4	-16	-4	11	90	35	-7	-265
5	0	0	0	0	0	0	0	0
5	1	-1	11	2	-22	4	1	16
5	2	1	3	8	-23	1	-5	125
5	3	-5	5	1	23	-4	-7	-123
5	4	1	-10	10	1	9	-3	-107
5	5	4	3	-2	-25	-2	-7	77
6	0	0	0	0	0	0	0	0
6	1	2	-2	-3	-4	3	9	-14
6	2	-1	-1	1	6	1	3	106
6	3	1	0	-10	8	0	0	68
6	4	2	6	1	-26	-12	-2	-32
6	5	-2	3	-6	15	13	-4	-10
6	6	3	-4	3	-17	-12	-4	-13
7	0	0	0	0	0	0	0	0
7	1	-2	5	11	-16	-6	0	-57
7	2	0	-3	2	0	1	2	-27
7	3	2	-2	-2	-6	-1	-8	-8
7	4	2	-5	-1	3	-2	-4	9
7	5	-1	-3	1	8	1	-3	23
7	6	-1	3	-3	3	0	-5	-19
7	7	0	1	-4	4	-2	-5	-17
8	0	0	0	0	0	0	0	0
8	1	-1	7	-7	1	7	6	3
8	2	0	-1	6	-9	0	7	-13
8	3	-1	7	-4	-3	2	13	5
8	4	-2	3	1	6	5	-4	-17
8	5	1	-2	1	-6	-5	1	4
8	6	0	-3	2	4	4	-7	22
8	7	0	-1	7	-7	-7	-4	-3
8	8	-3	3	1	8	6	-9	-16

TABLE 5(b)

The IGRF was developed to fill the need for a standard field model in which the permanence of a standard over a period of years outweighs the advantages of a high accuracy. Thus, the ultimate use of this model and further requests for revisions must be left to the users.

The way to test the applicability of IGRF(10/68) to a particular problem is to perform regular tests of newer or more accurate models and compare the results with those based on IGRF. As the core field deviates more and more from the IGRF estimate, the accuracy will continuously decrease.

$\dot{g}$	$n$	$m$	GSFC(12/66)	AFCRL(3/68)	RGO-2	IZMIRAN	USCGS	RGO-1	IGRF
	1	0	-1.5	-3.3	1.7	3.3	-0.3	0.2	15.3
	1	1	0.7	-1.9	0.3	-1.0	1.8	-0.4	8.7
	2	0	0.3	-3.3	0.4	-0.7	3.3	-2.2	-24.4
	2	1	-0.5	-0.5	-1.3	-0.2	2.4	-1.6	0.3
	2	2	-4.2	-2.0	3.6	0.4	2.1	2.9	-1.6
	3	0	-1.7	0.1	-0.2	0.6	1.1	-0.2	0.2
	3	1	0.0	0.6	0.8	1.9	-3.3	1.3	-10.8
	3	2	1.7	0.5	-1.7	-0.7	0.2	-2.6	0.7
	3	3	-3.1	-3.0	2.8	2.1	1.3	3.2	-3.8
	4	0	2.1	1.4	-0.3	0.9	-4.1	1.3	-0.7
	4	1	0.5	0.6	-0.2	0.1	-1.0	0.8	0.2
	4	2	1.3	2.6	-1.0	0.7	-3.6	0.8	-3.0
	4	3	0.8	-0.4	1.1	0.1	-1.7	0.3	-0.1
	4	4	-1.4	1.2	-0.9	0.8	0.3	-0.9	-2.1
	5	0	-0.0	1.4	-0.9	-1.3	0.7	-1.1	1.9
	5	1	-0.5	-0.5	-1.1	-0.8	2.9	-0.7	1.1
	5	2	0.9	-0.2	0.1	-1.8	0.9	-1.3	2.9
	5	3	-0.6	-0.2	-1.6	-1.0	3.2	-0.9	0.6
	5	4	-0.6	1.5	-1.0	-0.7	0.8	-1.1	0.0
	5	5	0.8	2.7	-0.3	-1.2	-2.1	0.4	1.3
	6	0	-0.4	-1.1	0.1	-0.4	1.8	0.1	-0.1
	6	1	1.2	-0.7	0.3	0.6	-1.3	-0.2	-0.3
	6	2	-0.2	-0.6	-0.1	-0.4	1.2	0.7	1.1
	6	3	0.7	-0.7	0.1	-0.6	0.4	-0.5	1.9
	6	4	1.2	0.9	0.4	0.8	-3.4	1.0	-0.4
	6	5	0.6	-2.3	0.4	0.4	0.9	0.6	-0.4
	6	6	0.6	0.6	-0.8	0.2	-0.6	-2.0	-0.2
	7	0	-0.1	0.7	0.5	0.5	-1.6	0.5	-0.5
	7	1	-0.0	-0.0	0.3	0.3	-0.6	0.3	-0.3
	7	2	-0.9	-0.3	0.7	0.7	-0.2	0.7	-0.7
	7	3	-0.4	1.3	0.5	0.5	-1.9	0.5	-0.5
	7	4	-0.3	-0.8	-0.3	-0.3	1.5	-0.3	0.3
	7	5	-0.7	-0.7	0.0	0.0	1.4	0.0	-0.0
	7	6	0.0	0.9	0.2	0.2	-1.3	0.2	-0.2
	7	7	-0.1	-1.6	0.6	0.6	0.5	0.6	-0.6
	8	0	0.3	-0.3	-0.1	-0.1	0.3	-0.1	0.1
	8	1	0.1	-0.1	-0.4	-0.4	0.8	-0.4	0.4
	8	2	1.3	-0.5	-0.6	-0.6	0.3	-0.6	0.6
	8	3	-0.2	-0.8	-0.0	-0.0	1.1	-0.0	0.0
	8	4	0.5	-0.8	0.0	0.0	0.2	0.0	-0.0
	8	5	-0.0	-0.1	0.1	0.1	-0.0	0.1	-0.1
	8	6	0.2	-0.7	-0.3	-0.3	1.1	-0.3	0.3
	8	7	0.1	-1.4	0.3	0.3	0.6	0.3	-0.3
	8	8	0.0	-0.4	0.5	0.5	-0.6	0.5	-0.5

TABLE 5(c)

We have already made this test for the application to analysis of the time variations of the Cosmos 49, OGO 2, and OGO 4 data. For such studies the IGRF is not useful, the GSFC(12/66) model is insufficient, and fits based on the data themselves are being used. For higher accuracy studies, we suggest using the GSFC(12/66) model over the range 1900-1965 and the POGO(10/68) model for 1965-1968. Beyond 1968, POGO(10/68) can be used until it is updated by more recent data and planned improvements in the analysis.



$n$	$h$ $m$	GSFC(12/66)	AFCRL(3/68)	RGO-2	IZMIRAN	USCGS	RGO-1	IGRF
1	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	1	-1.7	1.4	2.3	-0.2	-1.7	2.9	-2.3
2	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1	-2.3	-4.1	-0.2	2.0	4.7	0.4	-11.8
2	2	0.0	1.3	-1.3	0.9	-1.1	-1.5	-16.7
3	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	1	1.5	0.8	0.8	0.1	-3.1	-1.0	4.2
3	2	1.8	1.4	0.3	0.0	-3.7	0.9	0.7
3	3	1.1	-3.3	-1.3	2.1	1.5	-0.8	-7.7
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1	-2.1	-1.4	1.1	1.5	1.0	3.1	-0.1
4	2	-1.4	-3.0	-0.6	-0.7	5.7	-2.3	1.6
4	3	-1.2	-0.2	0.1	-0.4	1.7	-0.2	2.9
4	4	-2.6	-0.3	1.2	2.6	-0.8	1.5	-4.2
5	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	1	-0.3	-0.1	-0.3	-1.9	2.6	-0.4	2.3
5	2	-0.1	0.5	0.3	-0.3	-0.3	0.6	1.7
5	3	-0.3	0.6	0.4	1.2	-1.9	0.6	-2.4
5	4	-0.3	-2.6	0.2	-0.6	3.4	0.6	0.8
5	5	0.1	0.2	0.3	0.5	-1.1	0.8	-0.3
6	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	1	1.1	0.5	-1.1	0.5	-1.0	-1.3	-0.9
6	2	0.4	0.5	1.4	0.6	-2.9	0.6	-0.4
6	3	0.6	-0.1	-0.0	-1.1	0.8	-1.1	2.0
6	4	-0.3	1.3	0.1	1.1	-2.1	-1.0	-1.1
6	5	0.4	0.5	-0.1	-0.1	-0.7	-0.2	0.1
6	6	-0.1	-1.3	0.1	-0.9	2.3	-1.1	0.9
7	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	1	0.1	0.5	1.1	1.1	-2.7	1.1	-1.1
7	2	-0.2	-1.1	-0.3	-0.3	1.9	-0.3	0.3
7	3	0.1	0.5	-0.4	-0.4	0.2	-0.4	0.4
7	4	0.6	-0.6	-0.2	-0.2	0.4	-0.2	0.2
7	5	-0.8	-0.8	-0.4	-0.4	2.4	-0.4	0.4
7	6	0.4	1.5	-0.2	-0.2	-1.4	-0.2	0.2
7	7	0.7	1.1	-0.3	-0.3	-1.2	-0.3	0.3
8	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	1	-0.7	-0.4	-0.1	-0.1	1.3	-0.1	0.1
8	2	-0.1	-0.0	0.2	0.2	-0.2	0.2	-0.2
8	3	0.4	-0.7	0.3	0.3	-0.4	0.3	-0.3
8	4	-0.7	-0.2	0.2	0.2	0.5	0.2	-0.2
8	5	0.4	-0.1	0.3	0.3	-1.0	0.3	-0.3
8	6	0.5	0.2	0.4	0.4	-1.5	0.4	-0.4
8	7	-0.1	-1.0	0.3	0.3	0.5	0.3	-0.3
8	8	-0.2	-0.4	0.3	0.3	0.1	0.3	-0.3

TABLE 5(d)

The magnetic field derived from the IGRF or other magnetic field coefficients can be calculated from a wide variety of computer programs currently available. One such set of programs, based on a code originally developed by Jensen and Whitaker (1960), may be obtained from

World Data Center A for Rockets and Satellites  
Goddard Space Flight Center (601)  
Greenbelt, Maryland 20771

Table 6--Final IGRF(10/68) coefficients.

		EPOCH = 1965.0		I.G.R.F.(10/68)	
<i>n</i>	<i>m</i>	<i>g</i>	<i>h</i>	<i>ġ</i>	<i>ḣ</i>
1	0	-30339	0	15.3	0.0
1	1	-2123	5758	8.7	-2.3
2	0	-1654	0	-24.4	0.0
2	1	2994	-2006	0.3	-11.8
2	2	1567	130	-1.6	-16.7
3	0	1297	0	0.2	0.0
3	1	-2036	-403	-10.8	4.2
3	2	1289	242	0.7	0.7
3	3	843	-176	-3.8	-7.7
4	0	958	0	-0.7	0.0
4	1	805	149	0.2	-0.1
4	2	492	-280	-3.0	1.6
4	3	-392	8	-0.1	2.9
4	4	256	-265	-2.1	-4.2
5	0	-223	0	1.9	0.0
5	1	357	16	1.1	2.3
5	2	246	125	2.9	1.7
5	3	-26	-123	0.6	-2.4
5	4	-161	-107	0.0	0.8
5	5	-51	77	1.3	-0.3
6	0	47	0	-0.1	0.0
6	1	60	-14	-0.3	-0.9
6	2	4	106	1.1	-0.4
6	3	-229	68	1.9	2.0
6	4	3	-32	-0.4	-1.1
6	5	-4	-10	-0.4	0.1
6	6	-112	-13	-0.2	0.9
7	0	71	0	-0.5	0.0
7	1	-54	-57	-0.3	-1.1
7	2	0	-27	-0.7	0.3
7	3	12	-8	-0.5	0.4
7	4	-25	9	0.3	0.2
7	5	-9	23	-0.0	0.4
7	6	13	-19	-0.2	0.2
7	7	-2	-17	-0.6	0.3
8	0	10	0	0.1	0.0
8	1	9	3	0.4	0.1
8	2	-3	-13	0.6	-0.2
8	3	-12	5	0.0	-0.3
8	4	-4	-17	-0.0	-0.2
8	5	7	4	-0.1	-0.3
8	6	-5	22	0.3	-0.4
8	7	12	-3	-0.3	-0.3
8	8	6	-16	-0.5	-0.3

These programs internally convert the Schmidt-normalized coefficients to a more efficient Gauss-normalized form, update them to the epoch requested, and compute the geocentric components from the scalar gradient of the potential function, given the geocentric position. Conversions are also provided from geodetic position to geocentric, as well as routines for rotating the output geocentric components into geodetic directions. Ignoring the differences between geodetic and geocentric coordinates will create errors up to about 200γ.

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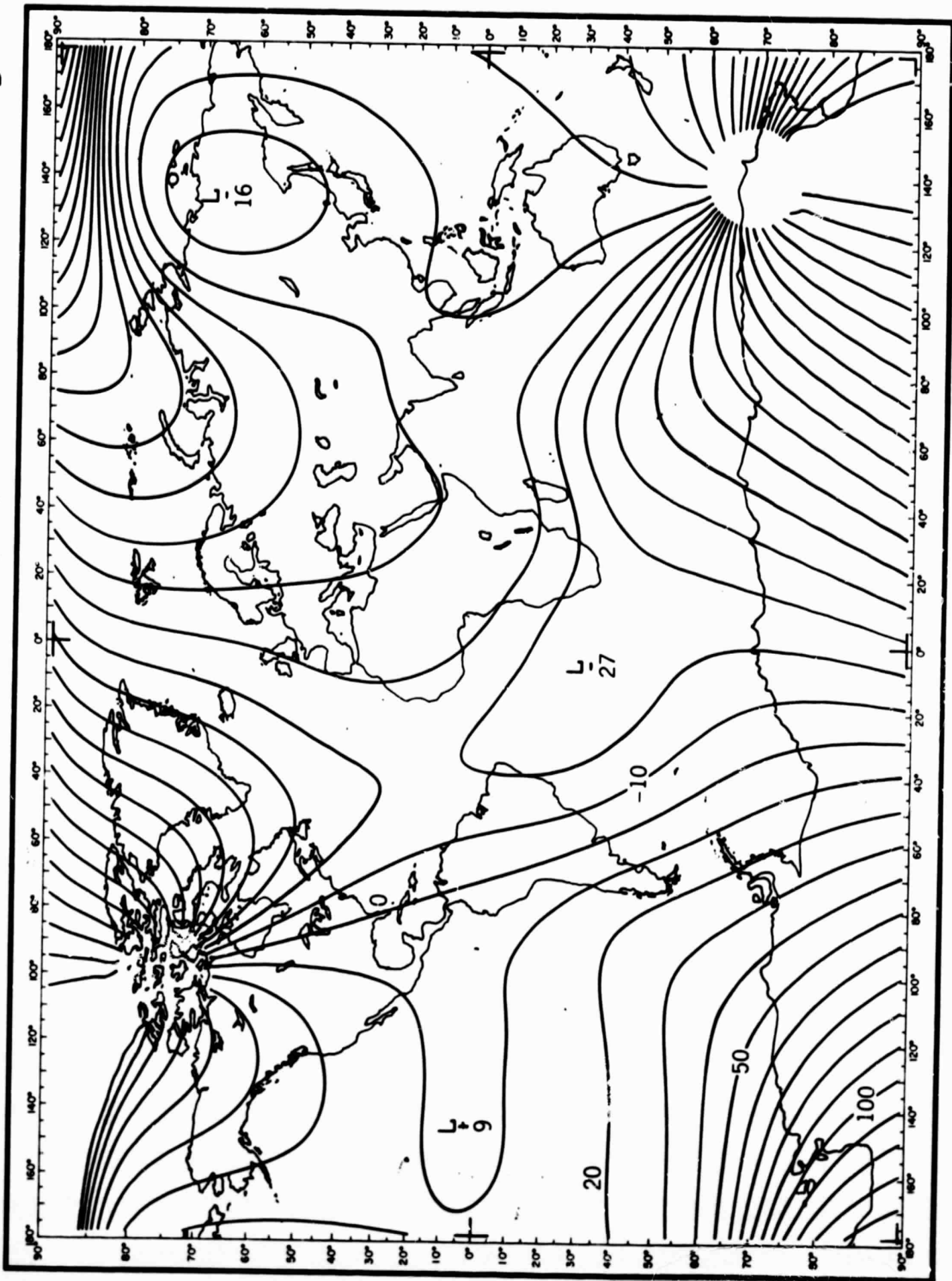
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## Appendix 1

### **Main Field Component and Isoporic Charts Computed From IGRF(10/68) for 1965.0 at the Earth's Surface**

The following figures represent the surface contours of the various geodetic components of the geomagnetic field and its secular change as computed by the IGRF. These diagrams are very similar to those given by Cain and Hendricks (1968) for the GSFC(12/66) field and are drawn automatically using a computer program originally used for weather maps (Cain and Neilon, 1963).

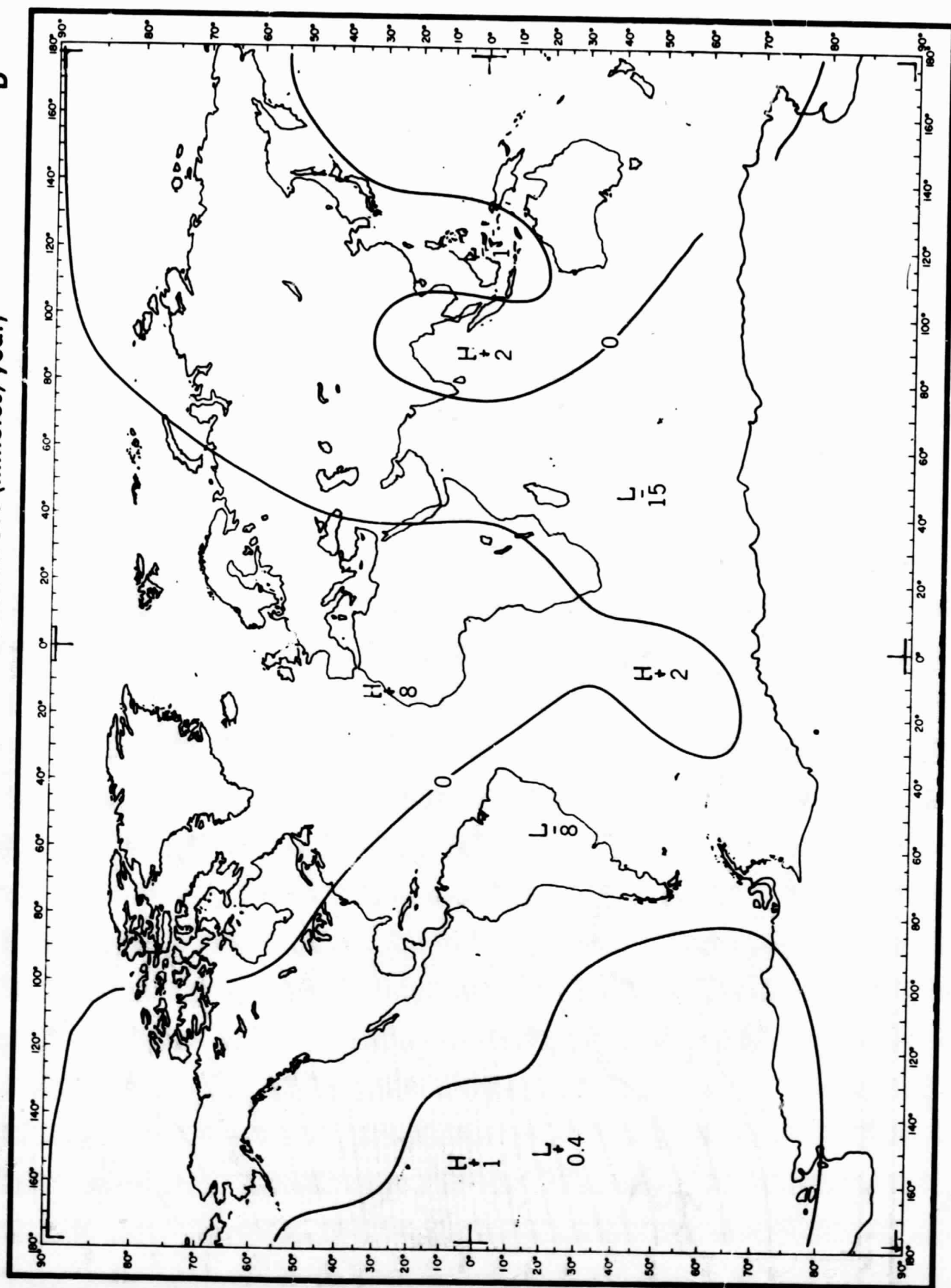
The plots are thus drawn to include the algebraic "lows" and "highs" of the component being displayed. These extrema occur at the center of the "+" or "-" symbols. The dip poles are noted for the H chart as "⊗".



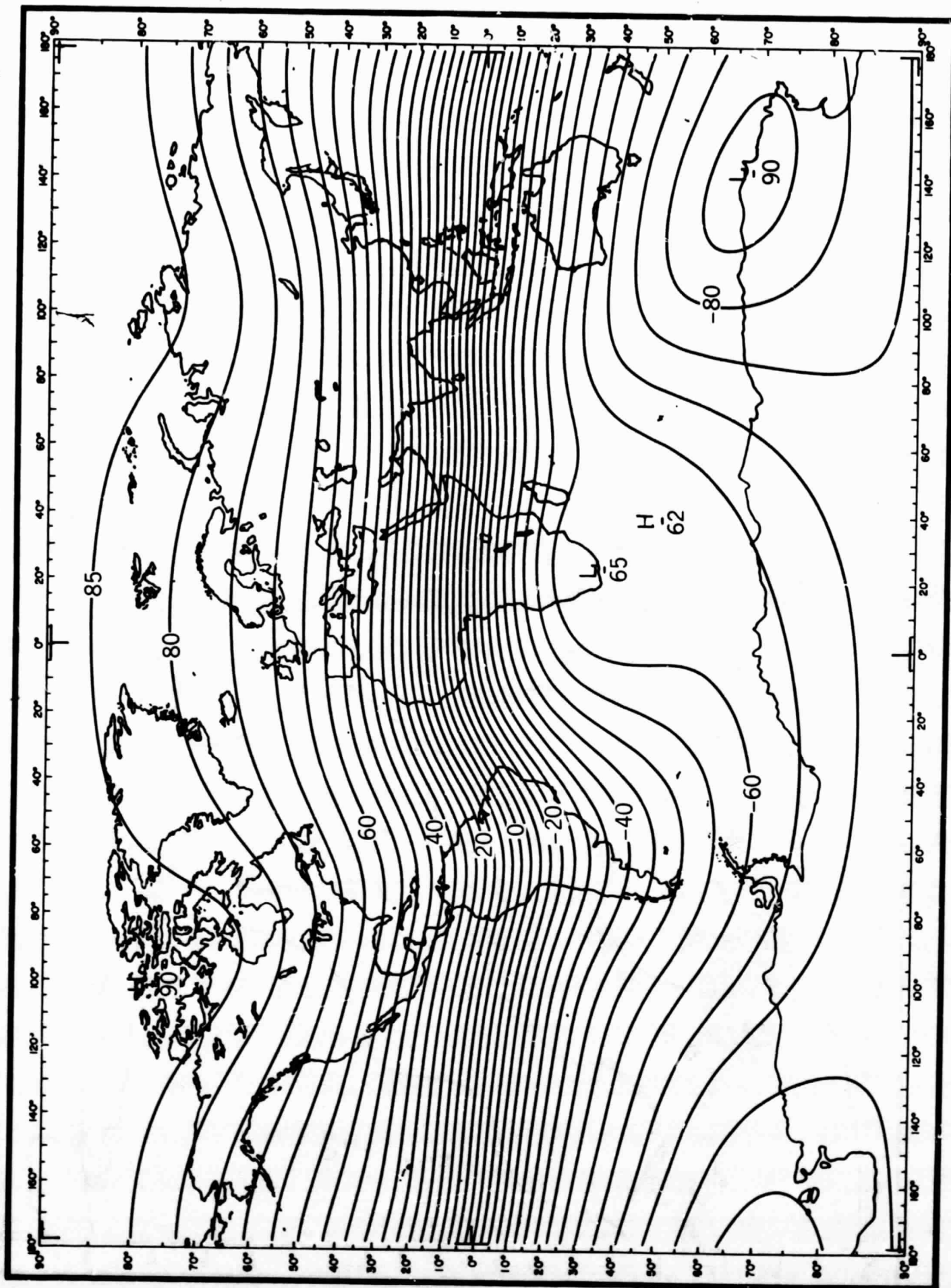


D

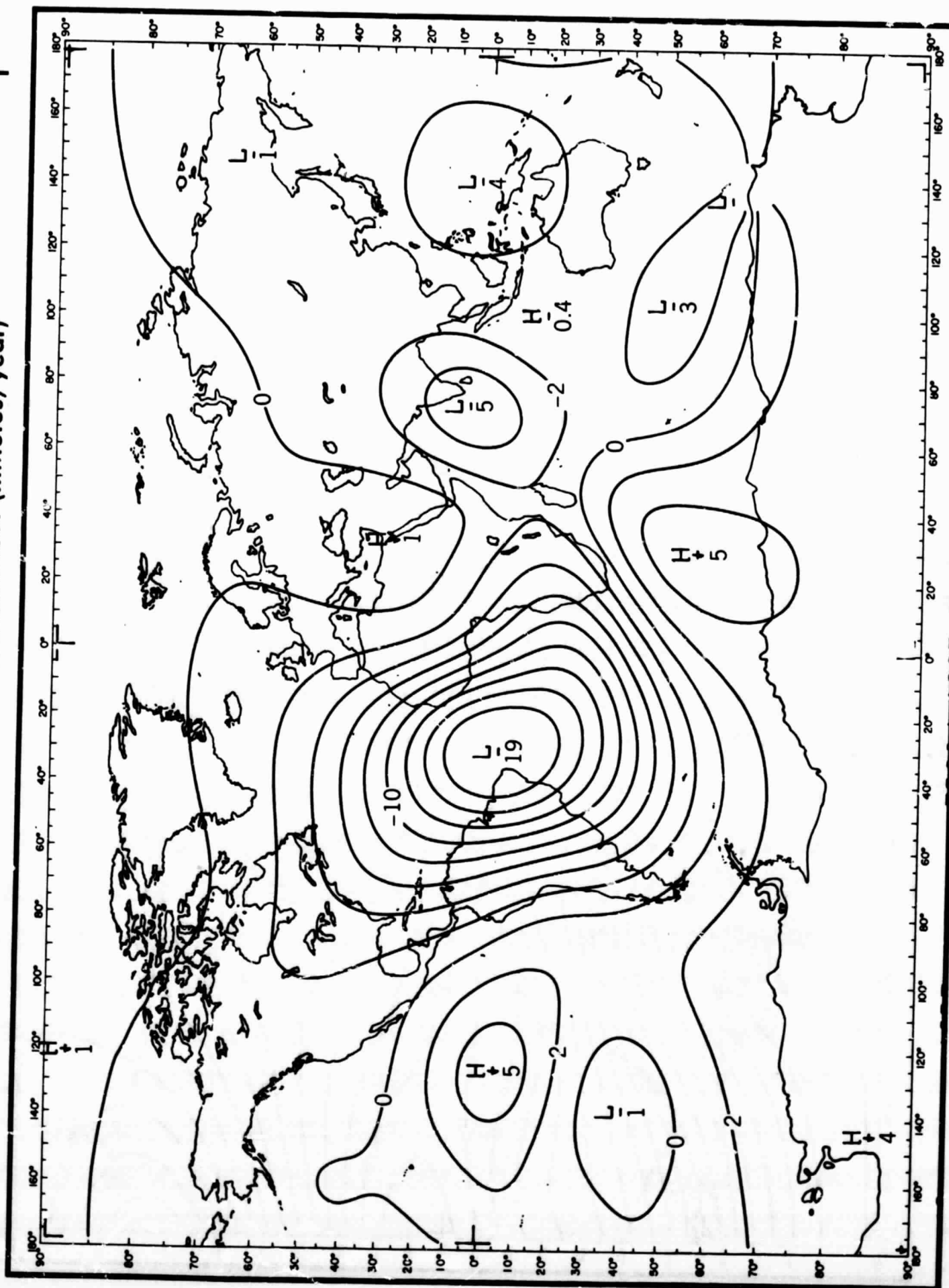
# SECLAR CHANGES OF DECLINATION (minutes/year)



INCLINATION (degrees)

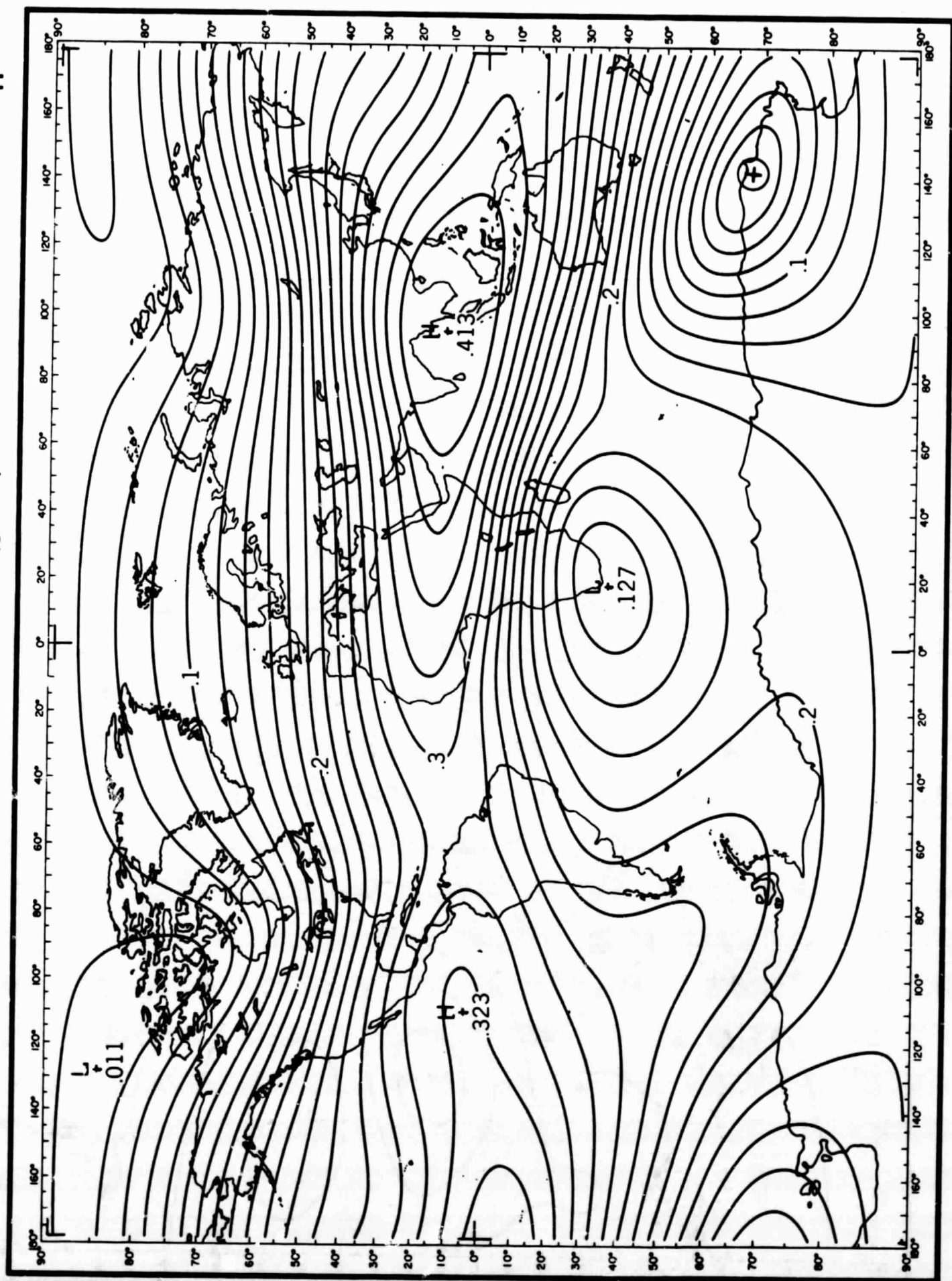


# SECCULAR CHANGES OF INCLINATION (minutes/year)

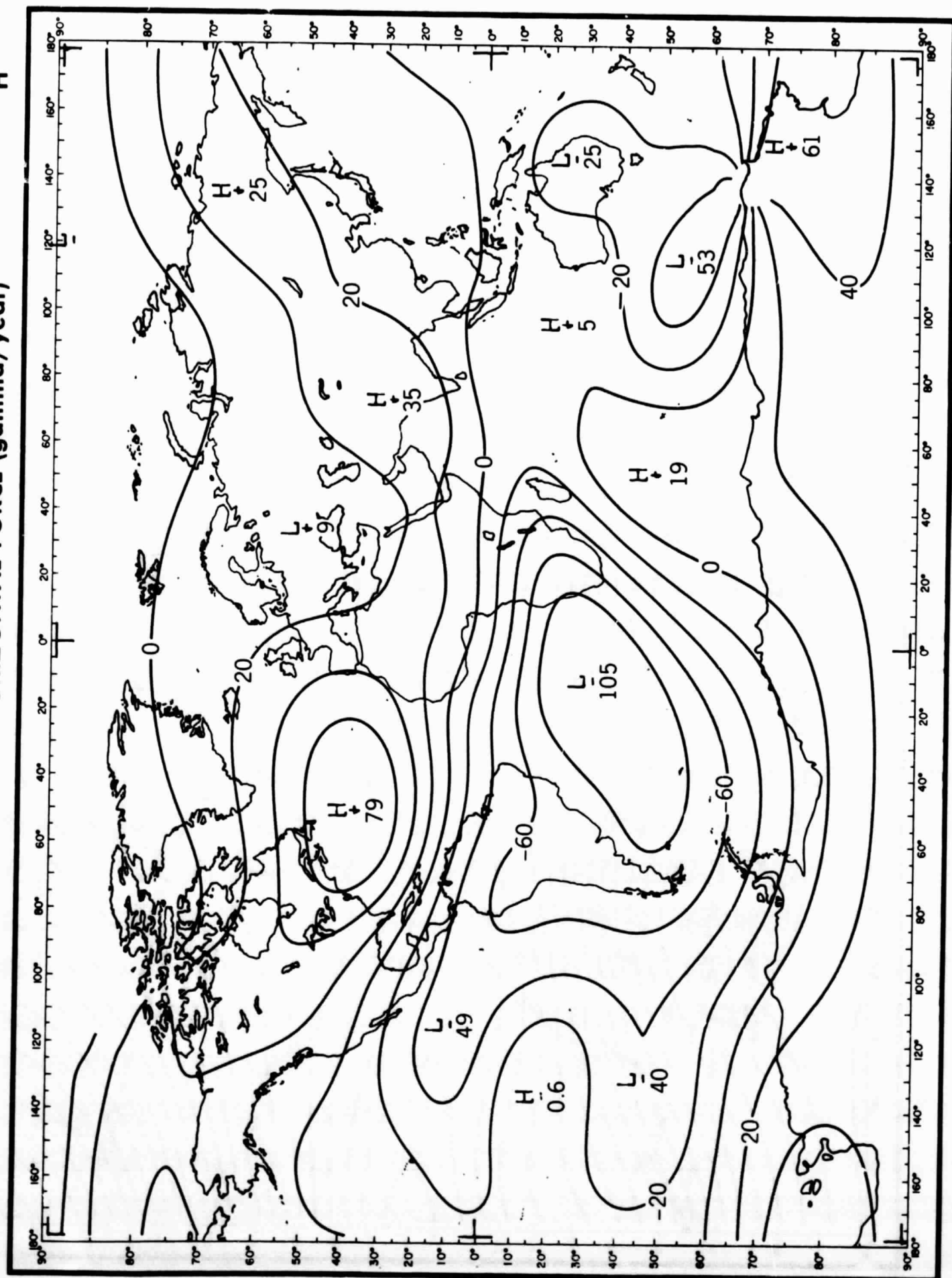


HORIZONTAL FORCE (gauss)

H



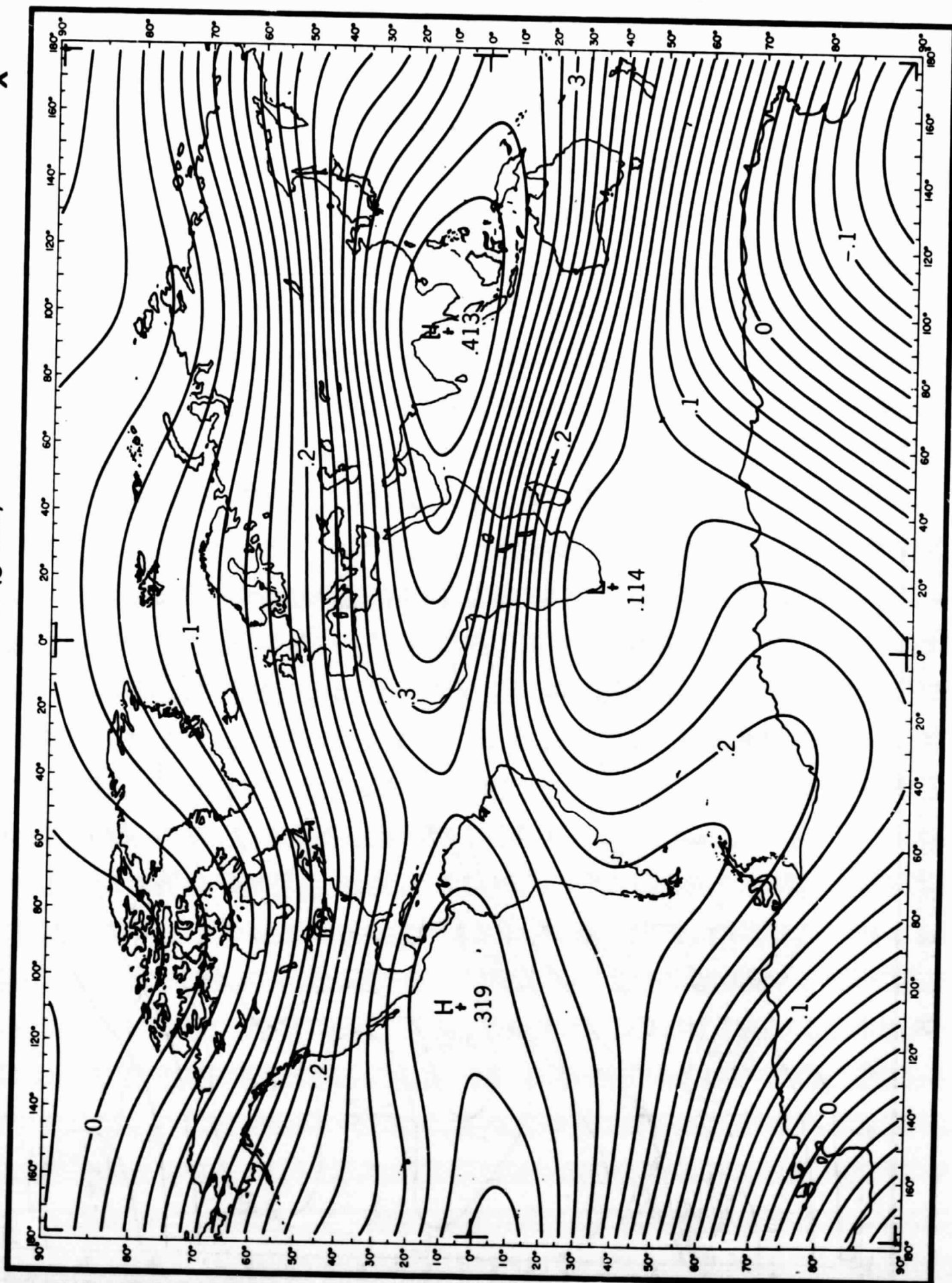
# SECCAR CHAGE OF HORIZENTAL FORCE (gamma/year)





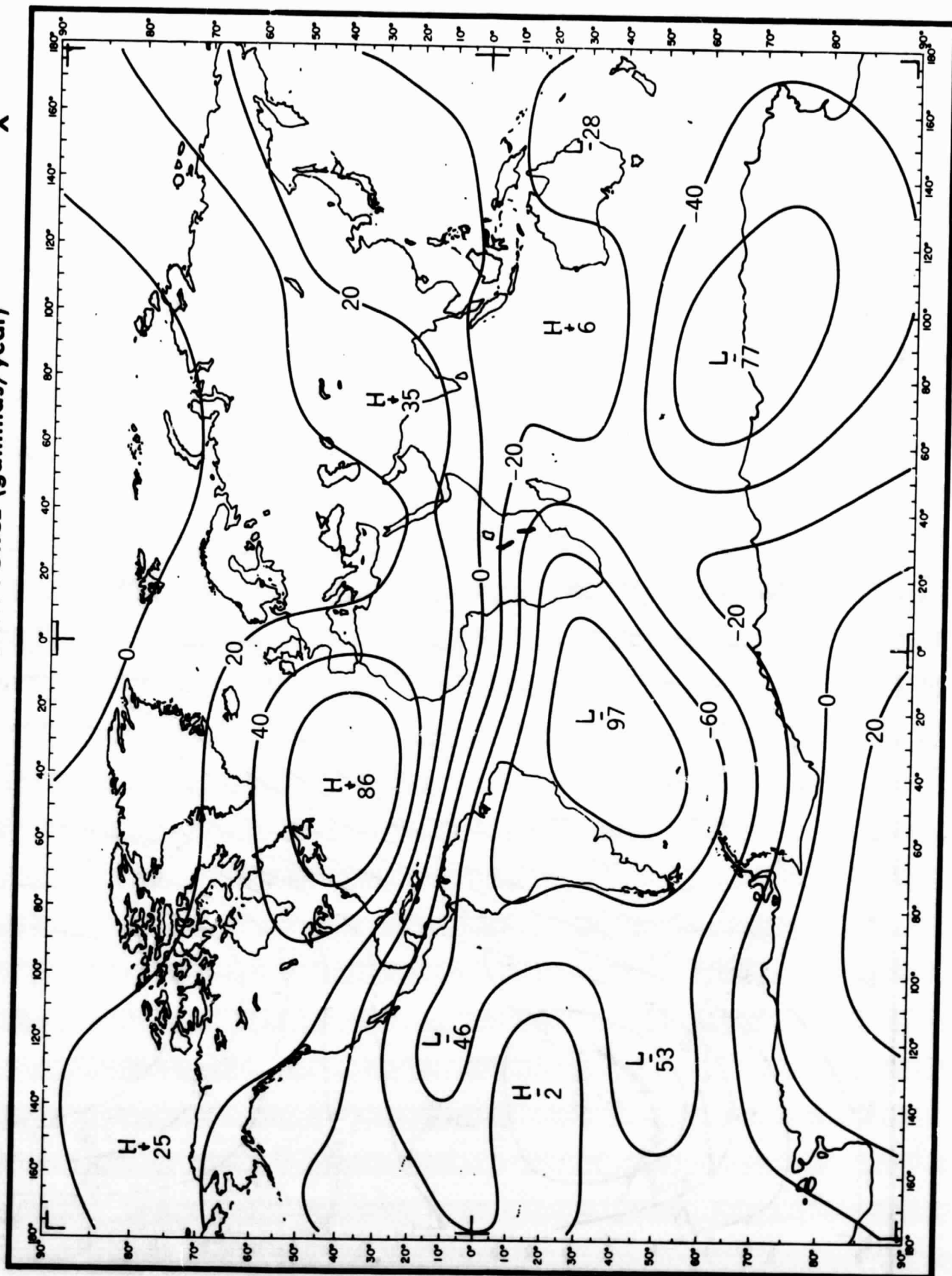
# NORTH FORCE (gauss)

X



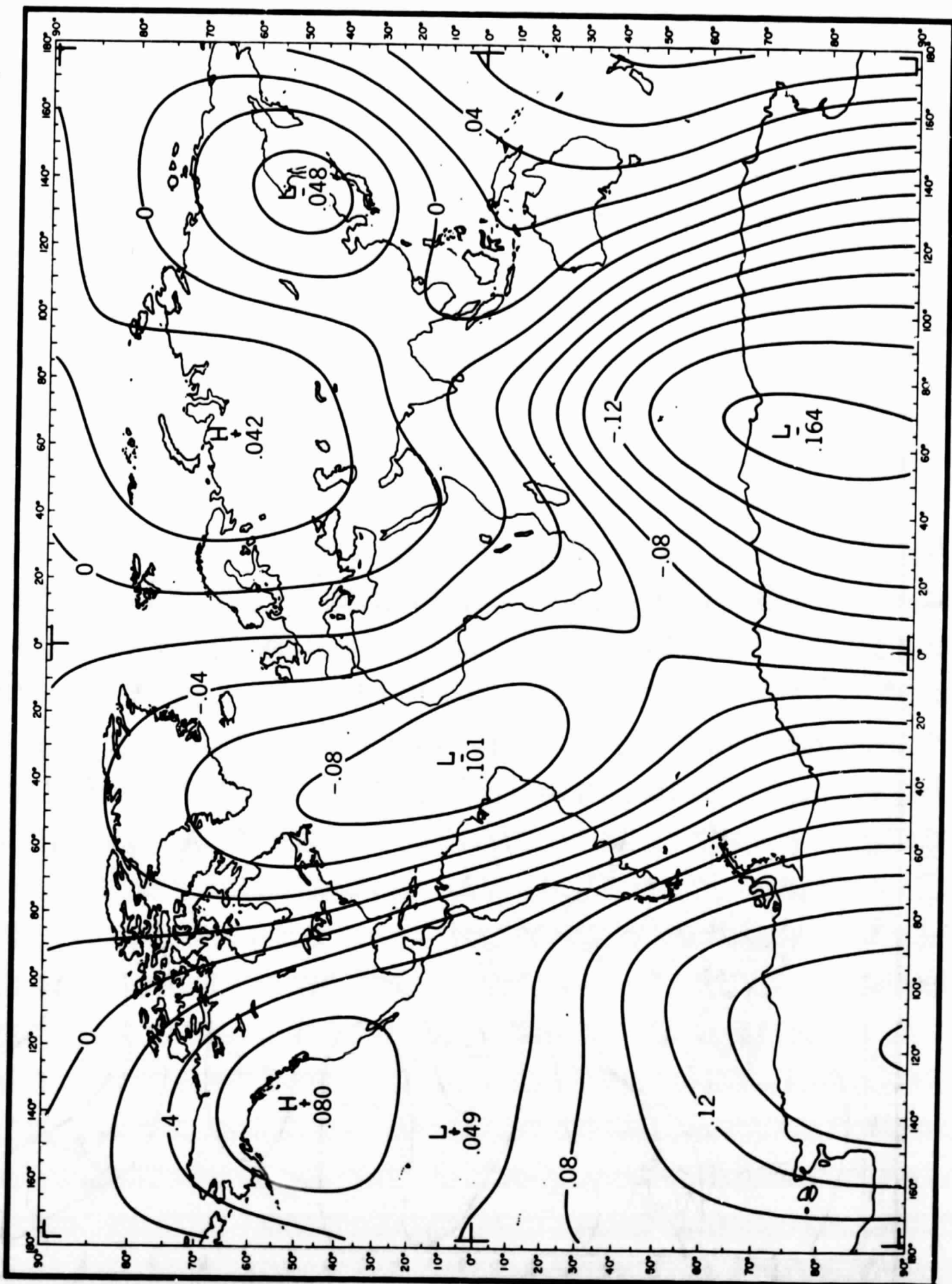
# SECULAR CHANGE OF NORTH FORCE (gammas/year)

• X

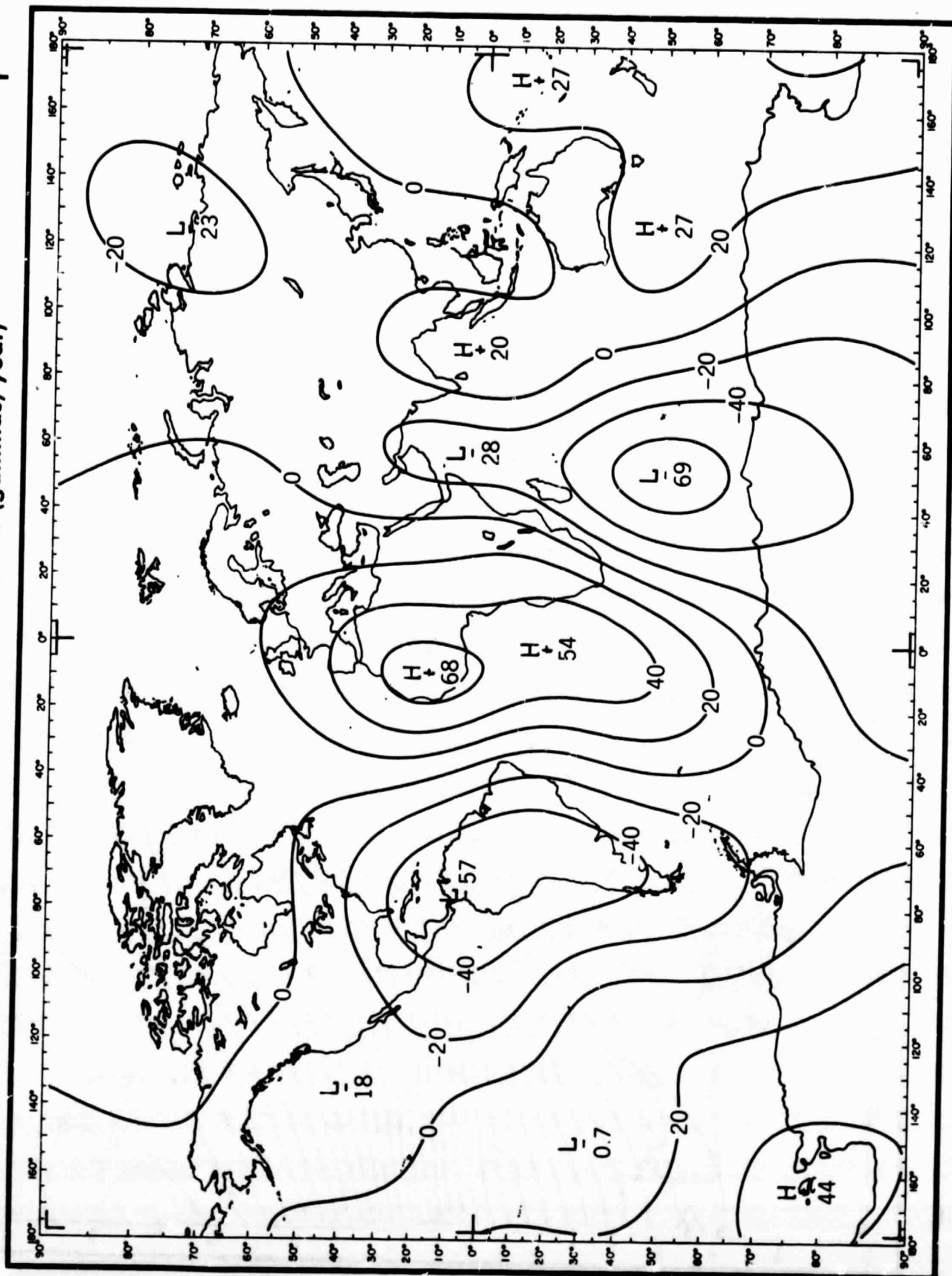


# EAST FORCE (gauss)

Y



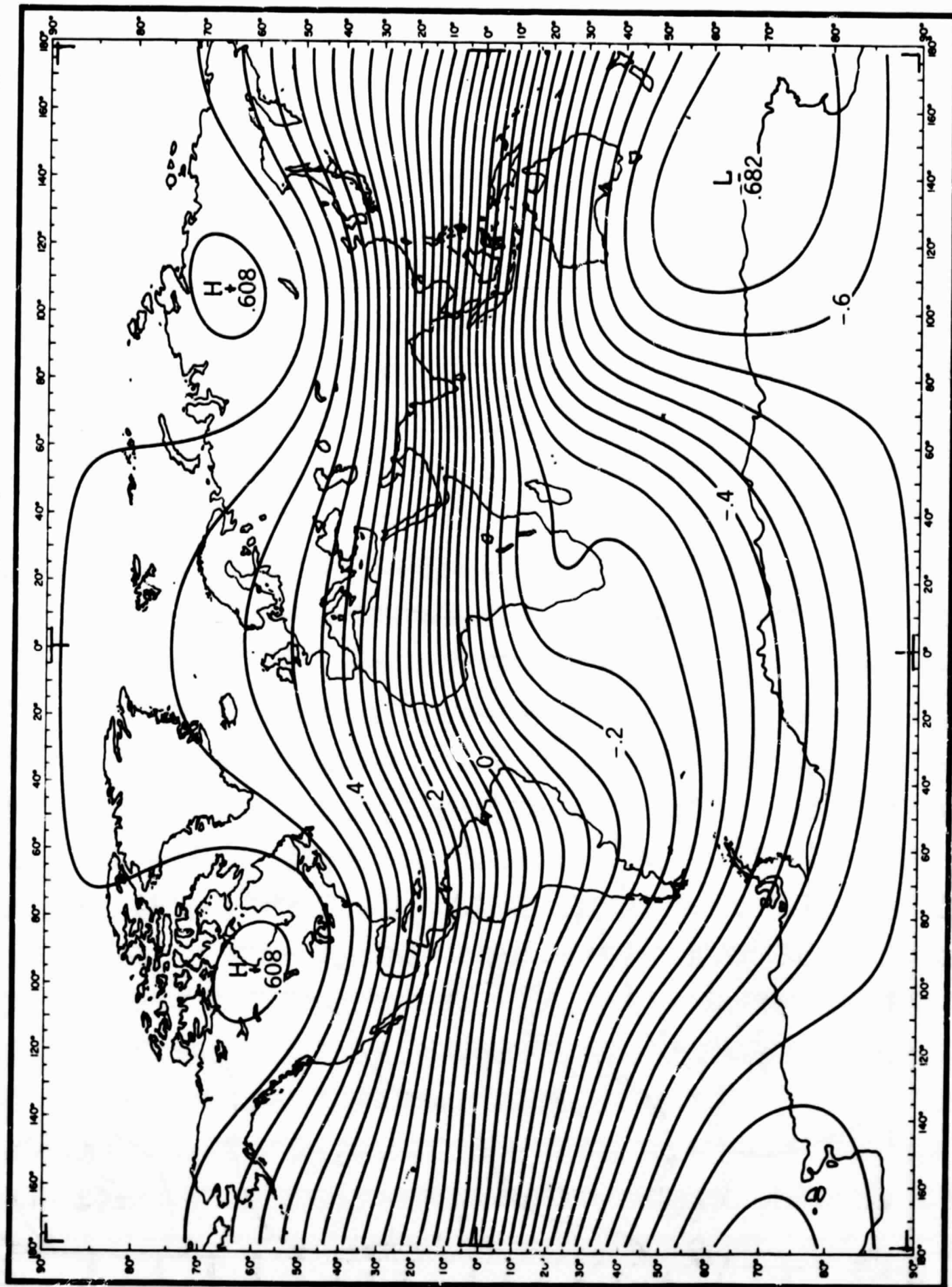
# SECCULAR CHANCE OF EAST FORCE (gammas/year)





# VERTICAL FORCE (gauss)

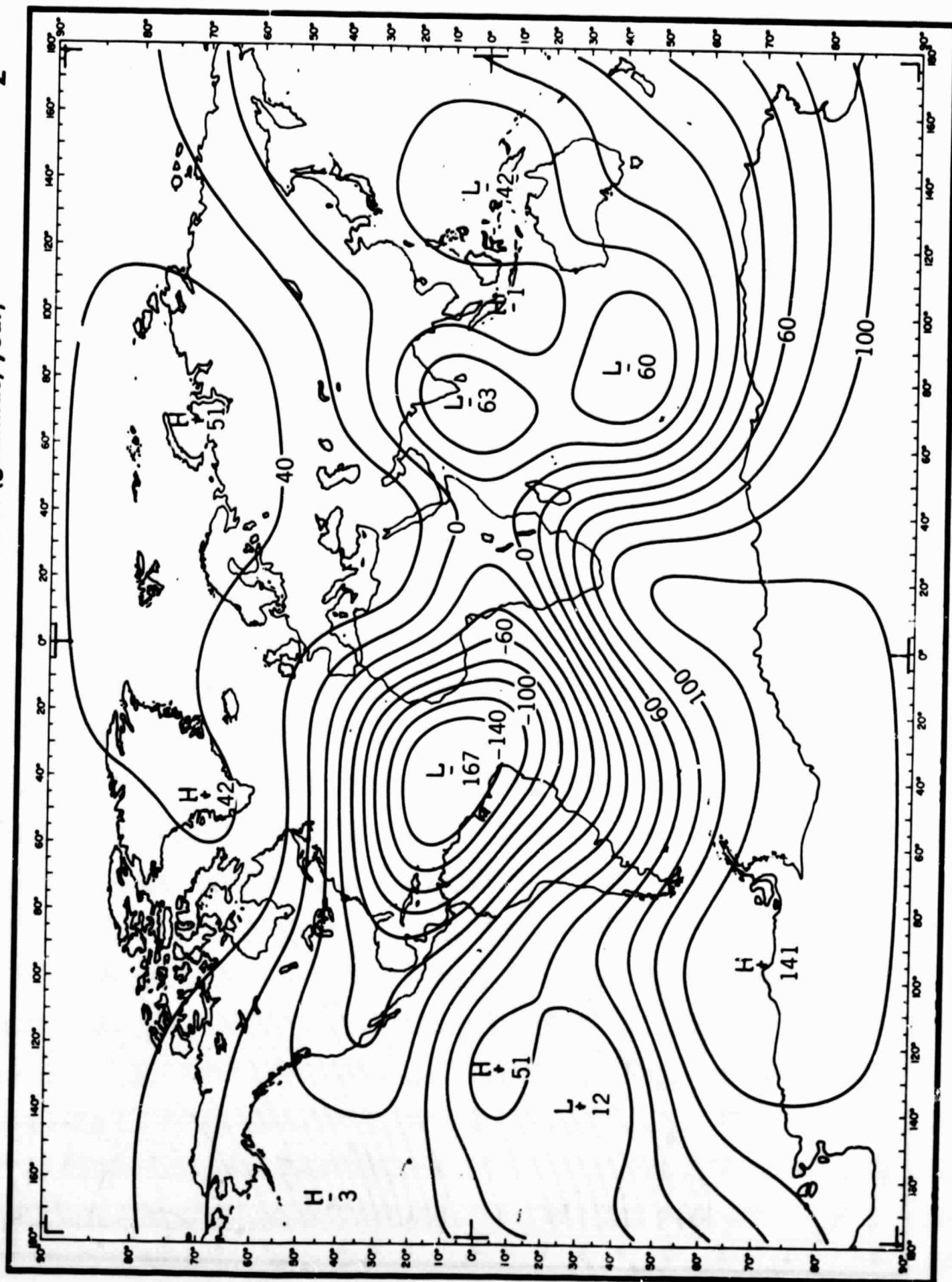
Z





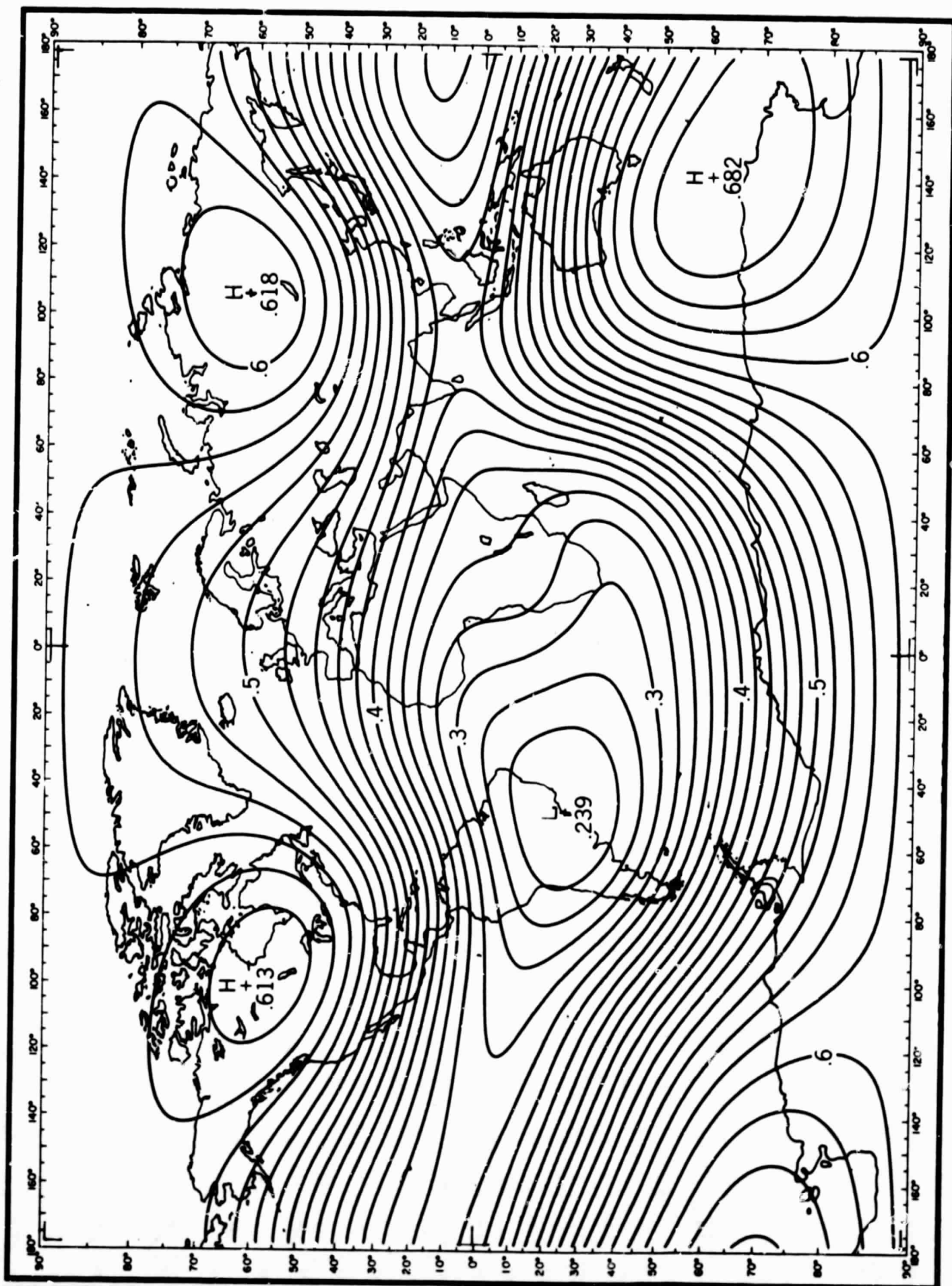
# SECLAR CHANGE OF VERTICAL FORCE (gammas/year)

z

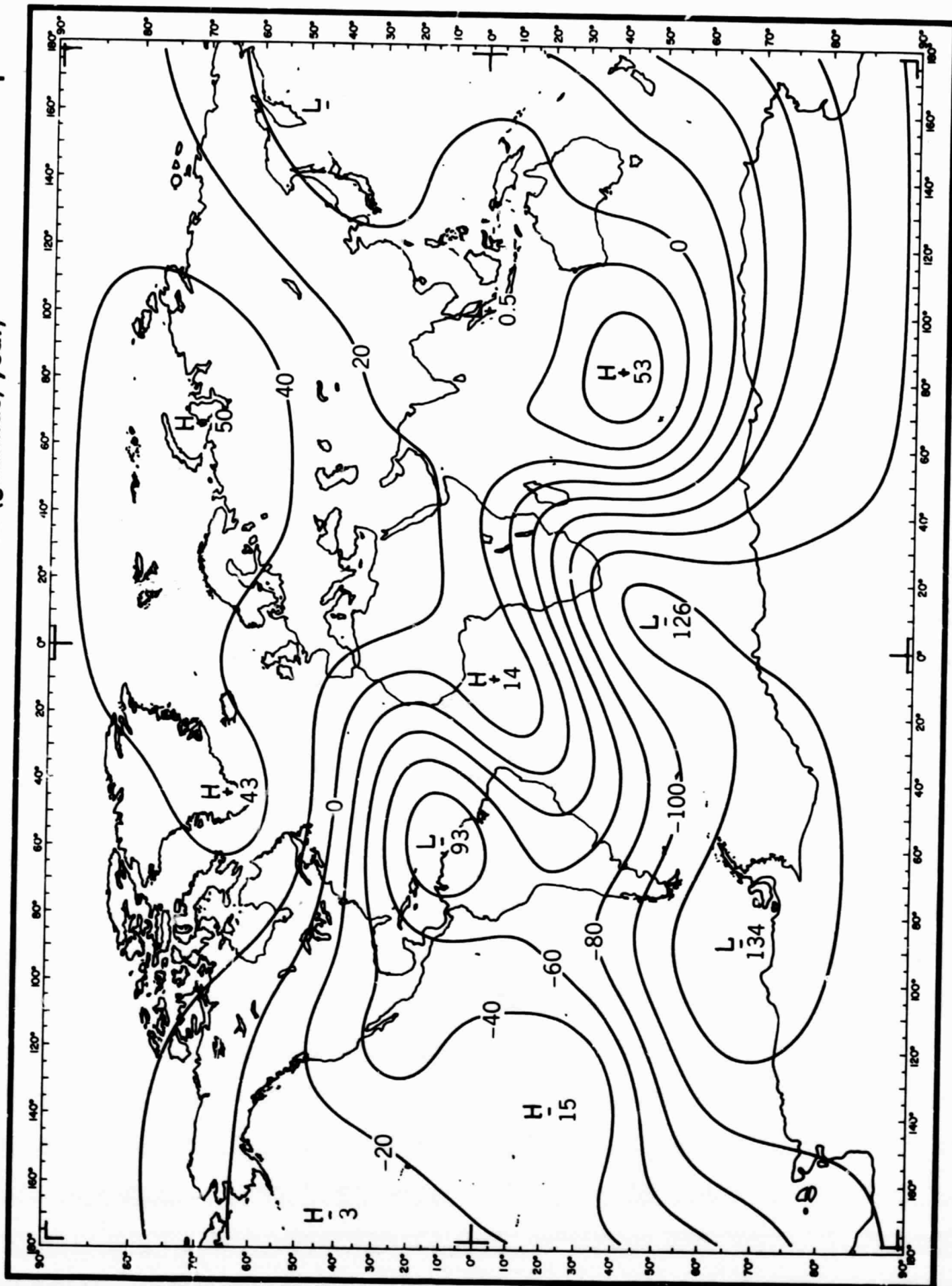


# TOTAL FORCE (gauss)

F



# SECLAR CHANGE OF TOTAL FORCE (gammas/year)



## Appendix 2

### Coefficient Normalization

All of the previous field derivations have arbitrarily set the earth's mean radius at 6371.2 for the value of  $a$  in the factors  $(a/r)^{n+1}$  of the potential expansion. This value stemmed from the old standard earth constants with equatorial radius 6378.388 and flattening 1/297. However, the new constants have become 6378.165 and 1/298.25 respectively. Integrating

$$\bar{r} = \int_0^{\pi/2} r \cos \theta d\theta ,$$

we obtain

$$\bar{r} = \frac{a}{m} \ln \left( \frac{m+a}{b} \right) ,$$

where

$$m = \sqrt{\frac{a^2 - b^2}{b}} ,$$

$a$  = equatorial radius,

and

$b = a(1 - f)$  is the polar radius with  $f$  the flattening factor.

The values with the old and new constants are as follows.

$f$	$a$	$b$	$\bar{r}$
297	6378.39	6356.91	6371.21
298.25	6378.16	6356.77	6371.02

It is recommended that for the sake of simplicity and not to be restricted to constants of only historical significance, we adopt the value of 6371 for  $a$ . This is a very slight change and has only the effect of altering the  $g_1^0$  term from -30,339 to -30,342 and the  $h_1^1$  term from 5758 to 5759. The constants  $\alpha$  used to make the correction  $g = g' + \alpha g'$ , where  $g'$  is the old value of  $g$  or  $h$ , are

$n$	1	2	3	4	5	6	7	8	9	10	11	12
$\alpha \times 10^5$	9	13	16	19	22	25	28	31	35	38	41	44

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